Spring Cleaning:
A Randomized Evaluation of Source Water Quality Improvement*

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Abstract: Water-related diseases, particularly diarrhea in young children, kill two million people annually. To address this problem, donors and governments often provide infrastructure such as communal standpipes, wells, and protected springs in rural areas, where piping water into homes is infeasible. We study the impact of source water quality improvements achieved via spring protection in rural Kenya using a randomized evaluation. Spring protection leads to large improvements in source water quality as measured by the fecal indicator bacteria *E. coli*. Water quality gains at the home are smaller, and depend critically on households' water source choices. At households that only used the sample spring at baseline, 65% of the spring water quality benefits are translated into home water gains, suggesting that re-contamination in transport and storage may be less of a concern than is sometimes claimed. Consistent with this view, the home water quality gains of spring protection are no larger for households with better baseline sanitation or hygiene knowledge. Households increase their use of springs, but other behaviors do not change after spring protection. Changes in household water source choices after spring protection are used to derive revealed preferences estimates of the willingness to pay for improved water quality using a travel cost approach. We find no significant child health effects of spring protection.

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1 Introduction

The sole quantitative environmental target in the United Nations Millennium Development Goals (MDGs) is the call to "reduce by half the proportion of people without sustainable access to safe drinking water" (General Assembly of the United Nations 2000). Meeting this goal will require providing over 900 million people in rural areas of less developed countries with either household water connections, which are often impractical because of dispersed settlement, or access within one kilometer to a constructed public water point (standpipe, borehole with hand pump, protected spring, protected well or rainwater collection point).[1]

A central rationale for promoting safe drinking water is the persistently high level of water-related morbidity and mortality in less developed countries. The global health burden of diarrheal disease in particular is tremendous and falls disproportionately on young children. Diarrheal disease, the third leading cause of infant mortality following malaria and respiratory infections, kills approximately 2 million people annually and accounts for perhaps 20% of deaths among children under age five (Kosek *et al.* 2003). Diarrheal diseases are transmitted via the fecal-oral route, meaning that they are passed by drinking or handling microbiologically unsafe water that has been in contact with human or animal waste, or because of insufficient water for washing and bathing.

However, there remains active debate and little conclusive evidence regarding how best to tackle this scourge. To start, it remains unclear whether investing in the water sector is even the most effective way of reducing the diarrheal disease burden. Randomized trials have established that several health interventions—including increased breastfeeding, immunization, oral rehydration therapy (ORT), and micronutrient supplementation—are both effective and cost-effective in

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[1] Currently about US$10 billion is spent annually to improve water and sanitation in less developed countries (United Nations 2003), through numerous initiatives, such as the US$1 billion European Union Water Facility. In rural Africa, these funds are overwhelmingly spent on providing community-level resources like water taps or shared wells (UN-Water/Africa 2006). Among the US$5.5 billion the World Bank invested in rural water and sanitation programs from 1978-2003, nearly all focused on improving source water supply and quality through interventions such as well-digging and spring protection, while 3% went to sanitation improvements, less than 1% on hygiene promotion, and only a small portion to household point-of-use (POU) interventions (Iyer *et al*. 2006).

preventing diarrhea (see Hill *et al*. 2004).[2] Rotavirus kills about 600,000 children annually and although a vaccine exists few children receive it in the poorest countries.

Even within the environmental health sector, there is little consensus on the relative cost-effectiveness of different water, sanitation, and hygiene interventions when piping water into homes is impractical. For instance, there remains debate about whether improving water quality at the source, increasing the quantity of water available, or point-of-use (in home) treatment of microbial contaminants is most cost-effective. While several studies from the 1980s find that source water quality interventions reduce diarrheal morbidity, a recent strand of the academic literature has increasingly emphasized the importance of water quality at the point-of-use (POU). The efficacy of POU treatment has been convincingly demonstrated in several settings, but it is unclear whether most households are willing to use such treatments, and how much they are willing to pay for them. In the face of this ongoing debate, donor funding in the rural water sector continues to be overwhelmingly directed at source improvements.[3]

This paper evaluates the impact of source water quality improvements achieved via spring protection. Spring protection seals off the source of a naturally occurring spring and encases it in concrete so that water flows out from a pipe rather than seeping from the ground, where it is vulnerable to contamination from surface runoff, improving water quality at an already existing

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[2] Exclusive breastfeeding of infants is widely accepted as a means of preventing diarrhea in infants up to six months of age and continued breastfeeding for older children is also protective (Raisler *et al.* 1999, Perera *et al.* 1999, WHO Collaborative Study Team 2000). Many public health experts believe vaccines have a valuable role to play in preventing at least two diarrheal diseases, rotavirus and cholera (Glass *et al.* 2004, WHO 2004). ORT appears to have been responsible for reductions in diarrheal mortality (Miller and Hirschorn 1995, Victora *et al.* 1996 and 2000). Micronutrient supplementation, including with zinc and vitamin A,has also been found to have positive impacts (Grotto 2003, ZICG 1999 and 2000, Black 1998, Ramakrishnan and Martorell 1998, Beaton *et al.* 1993).

[3] The current study is one component of a larger project by the authors examining the relationships among water quality at the source, point-of-use, water quantity, and health, which taken together may provide guidance on whether there is scope for some readjustment of funding priorities in the rural water sector.

source. This is a widely used technology in Sub-Saharan Africa (Mwami 1995, Lenehan and Martin 1997, UNEP 1998), though it is unsuitable for the most arid regions (UNEP 1998).[4]

Using a randomized impact evaluation approach, in which spring protection is phased-in across nearly 200 springs in a randomized order, we estimate impacts on source water quality, household water quality, child health, and on household water collection choices and other health behaviors. Our approach differs from the existing literature on source water quality interventions in several ways. First, unlike many other studies, we are able to isolate the impact of a single treatment rather than a package of services. Second, we use a randomized design and a large sample size, and are able to take intra-cluster correlation into account. Third, rather than assuming or simulating ex post contamination between the source and the home, we have detailed longitudinal data on water quality at both points, where water contamination is measured by the fecal indicator bacteria *E. coli*. We are thus able to directly assess the extent to which source water quality improvements at springs translate into household water quality gains, and to evaluate the claim that source water quality improvements are most valuable in the presence of pre-existing access to improved sanitation and hygiene practices.

In the second component of the analysis, we use data on how household behaviors – most importantly, the choice of water source – change in response to source water quality improvements in a context where many households can choose from among several different water sources. We develop a formal economic framework of water source choice, in which households trade-off the distance walked to a water source against water quality. This framework highlights the importance of understanding endogenous household sorting among water sources in the econometric analysis, and

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[4] Spring protection is generally undertaken by donors or the central governments in this region because both law and custom require that private landowners allow public access to water sources on their land, leaving little private incentive to improve a water source and recoup the cost of such an investment via the collection of user fees. Local community organizations or village-level governments also have difficulty coordinating on institutional arrangements that would overcome free-rider rider problems in the collection of user fees or contributions needed for infrastructure construction (school committees that fund local schools are one exception). These collective action problems mean that even investments with positive returns often fail to be made.

allows us to develop revealed preference estimates of average household willingness-to-pay for source water quality improvements using a conditional logit travel cost approach. To our knowledge this is the first such revealed preference estimate of household valuation for water quality improvements in a less developed country context.

In our first empirical result, we find that spring protection is very effective in improving the quality of water at the source. Among “sole-source users”, those households that collected all of their drinking water from the sample spring at baseline, spring protection is also highly effective at improving household water quality. The high degree of pass through from source water quality gains to the home in this subsample suggests that recontamination in transport and storage may be less of a concern in rural Africa than is sometimes claimed. The exogenous variation in source water quality caused by the spring protection program allows us to use an instrumental variables approach to address econometric concerns about both measurement error (in source water contamination levels) and omitted variables that could bias estimates of the correlation between source water quality and home water quality.

However, among the “multi-source users” – those households that collected at least some of their water from sources other than the sample spring at baseline – estimated gains in home water quality are much smaller. We find that these multi-source users dramatically shifted their water collection trips towards protected springs after the intervention. We show in the formal model of source water choice that this sorting may account for the lack of observed home water quality gains, to the extent that some alternative water sources are less contaminated than the sample springs. A possible implication is that programs improving all water sources in an area might have larger impacts on home water quality than programs that only improve a subset of sources. Alternatively, increasing the take-up of point-of-use water treatment may be desirable in contexts where improving all local water sources is costly.

In our data, there is little evidence that the limited home water quality gains we observe in the multi-source user sample are due to crowding out of other protective measures such as boiling drinking water or in-home chlorination. Nor does pre-program access to improved sanitation or hygiene knowledge appear to allow households to better translate source water quality improvements into household water quality gains, further evidence against extensive recontamination of water during transport and storage.

We find no evidence of spring protection impacts on the average health or nutrition of young children in treatment households, even up to 18 months of spring protection. Even for sole-source user households alone, a group that did experience home water quality gains, we do not find statistically significant impacts of spring protection on child health or nutrition outcomes, and this is true both for diarrhea, which is notoriously difficult to measure, as well as for child weight and height where gains should be more apparent. This finding is consistent with an epidemiological model in which the primary causes of diarrhea are not waterborne or where there are important threshold effects in the relationship between water quality and health.

We next estimate willingness to pay for improved source water by analyzing how multi-source user households change their choice of water source – and in particular, the distance they are willing to walk to collect water – in response to the improvements generated by spring protection, in a conditional logit discrete choice model. The figure could have a range of uses by those interested in either source water quality improvements or point-of-use technologies in rural Africa; for example providing guidance on the magnitude of feasible user-fees at communal water sources. The results indicate that the average valuation of spring protection is reasonably high, on the order of US$37 per household per year. This high valuation appears out of line with the minimal observed child health benefits of spring protection. In the second year of protection households' valuation for spring protected water is similar in magnitude, providing suggestive evidence that with time households did not increase their valuation of spring protection. Future research will provide further evidence on the evolution of household willingness to pay for cleaner water.

2 Related Literature

Two influential papers (Esrey 1996, Esrey *et al.* 1991) are frequently cited as evidence for the relative importance of sanitation investments and hygiene education over the provision of improved water quality (*e.g*. USAID 1996, Vaz and Jha 2001, World Bank 2002).[5] Esrey *et al.* (1991) attempt to separate the relative impacts of water supply, sanitation, and hygiene education interventions on diarrheal morbidity. They conclude that the median reduction in diarrheal morbidity from either sanitation supply or hygiene education provision is nearly twice the median reduction from an investment in water quality alone or an investment in water quantity and water quality together. Using multivariate regression analysis of household infrastructure status and diarrhea prevalence from several countries, Esrey (1996) reaches a similar conclusion: benefits of improved water quality occur only in the presence of improved sanitation, and only when a water source is present within the home (e.g., piped water). However, as a result of the observational nature of Esrey's (1996) data, these results are subject to omitted variable bias (confounding) of unknown magnitude.

More recent meta-analysis in the epidemiological literature (Fewtrell *et al*. 2005) reports that source water quality improvements, sanitation, and hygiene programs, along with point-of-use water treatment can all effectively reduce diarrhea, with point-of-use treatment the most effective of these interventions, in contrast to the conclusions in Esrey et al. (1991). Fewtrell *et al*. (2005) conclude that

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[5] Reviews on the health impact of environmental health interventions to combat diarrheal diseases include Blum and Feachem 1983, Esrey *et al.* 1985, Esrey and Habicht 1986, Esrey *et al.* 1991, Rosen and Vincent 1999, and Fewtrell *et al.* 2005). As Briscoe (1984) and Okun (1988) emphasize, the welfare gains associated with infrastructure provision can extend far beyond mortality and morbidity impacts: for example, women's time may be freed from water transportation duties and thus other activities facilitated. We formalize this idea below.

point-of-use water treatment may be more effective than source water quality interventions because of recontamination during transportation and storage. Similarly, Wright *et al*. (2004) analyze 57 studies that measured both source and in-home water quality, and conclude that improvements in source water quality are often compromised by post-collection contamination. However, these evaluations of source water quality investments remain less methodologically rigorous than evaluations of point-of-use water treatment.[6] Moreover, to our knowledge there is no study in which household water quality has been measured following exogenous variation in source water quality, and no direct comparisons of the effectiveness of point-of-use water treatment and source water quality interventions in the same study setting have been made. In this paper, we directly measure the extent to which source water quality using a longitudinal household dataset, and exploiting experimental variation in source water quality. Our future work will estimate effectiveness of point-of-use technologies in the same area.

We are also able to contribute to a second literature by developing a novel revealed preference estimate of willingness to pay for improved water quality in a less developed country context using a conditional logit estimation approach. Understanding the determinants of household water demand was a research focus in the 1990s, and contingent valuation studies sponsored by the World Bank in several countries estimated both average stated willingness to pay for household

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[6] There are just two prospective studies of source water quality interventions that suggest positive impacts of these interventions on child health. Aziz et al. (1990) study the impact of an intervention in Bangladesh that simultaneously provided multiple interventions, including water pumps, hygiene education, and latrines, to two intervention villages (820 households), and compare them with three control villages (750 households), separated by about five kilometers. The published article does not mention if these villages were randomly selected. Following the intervention children between six months and five years of age in the intervention area experienced 25% fewer episodes of diarrhea than those in the comparison area. An almost identical reduction was observed after pumps had been installed but prior to the construction of latrines, which is consistent with a small treatment effect of improved sanitation beyond that achieved by well construction.

Huttly et al. (1987) study the impact of the provision of borehole wells with hand-pumps, pit latrines, and health education on dracunculiasis (guinea worm disease), diarrhea, and nutritional status in Nigeria in 1983-86. The study compared three intervention villages (850 households) and two comparison villages (420 households). Because of implementation difficulties, their results largely reflect the effect of the installation of wells with pumps. The prevalence of wasting (defined as less than 80% of desirable weight-for-height) among children under three years of age declined significantly in the intervention villages. Generalizing the positive results in these studies to other settings is hampered by their small village-level sample sizes (both include only five villages in total), and the fact that they evaluate interventions that improved both water quality and quantity simultaneously (by providing wells).

piped water connections and the heterogeneity in this demand (World Bank Water Demand Research Team 1993).

However, the relative shortcomings of such stated preference contingent valuation approaches to measuring the use value of non-market goods are well-known (Diamond and Hausman 1994). Survey respondents in contingent valuation studies do not face a real budget constraint when telling survey enumerators their willingness to pay for hypothetical goods or services, and may strategically overstate their true valuation (to be polite, or in an attempt to influence a donor's future investment decision) or understate it, to reduce the probability that they will be expected to pay if the service is later provided. Even in the absence of strategic motives, quick introspection during a survey can fail to reveal how one will actually behave when real trade-offs must be made.

In part to overcome these limitations, several alternative approaches to eliciting willingness to pay based on actual behavior have been developed in environmental economics. One such revealed preference approach is the travel cost method, in which time costs (and other expenditures required to reach a site) are used to estimate the willingness to pay for an amenity (McFadden 1974, Phaneuf and Smith 2003). To our knowledge, the conditional logit estimate of willingness to pay that we develop below is the first such application of the travel cost approach to value improved drinking water quality in a less developed country context. In future work we plan to compare willingness to pay estimates using this revealed preference approach to contingent valuation estimates obtained in the same population, to assess how consistent these estimates are with each other.

Water choices in rural less developed country settings have been studied by Whittington, Mu, and Roche (1990) and Mu, Whittington, and Briscoe (1990), however neither accounts for the role of water quality in the source choice decision (they focus on quantity) and they explicitly rule out the use of multiple drinking water sources, which we find to be empirically important in our data.

3 Rural Water Project (RWP) overview and data

This section describes the intervention, randomization into treatment groups, and data collection.

3.1 Spring protection in western Kenya

Naturally occurring springs are an important source of drinking water in rural western Kenya. The region has land formations that allow the ground water to come to the surface regularly. The area of Kenya in which our study site is located is poor (agricultural wages range from US$1-2 per day) and few households have access to improved water services. Like most water resources in rural Kenya, springs are often located on private land but landowners are expected (by both custom and law) to allow public access for the purpose of collecting water.

Springs were selected from a universe of local unprotected springs by a non-governmental development organization, International Child Support (ICS). The NGO first obtained lists of all local unprotected springs from Government of Kenya Ministry of Water offices. NGO field and technical staff then visited each site to determine which springs were suitable for protection. Springs known to be seasonally dry, in months when the water table is low, were eliminated, as were sites with upstream contaminants (e.g., latrines, graves) in the catchment area.

From the remaining list of suitable springs, 200 were randomly selected (using a computer random number generator) to receive protection. These springs are in the Busia and Butere-Mumias districts (Figure 1), and Figure 2 summarizes the timing of the data collection and intervention.

The NGO planned for the water quality improvement intervention to be phased in over four years due to their financial and administrative constraints. For the purposes of this paper, although all springs will eventually receive protection, the springs protected in round 1 (January-April 2005) and round 2 (August-November 2005) are called the treatment springs and those to be protected in later years are called comparison springs. Springs were first stratified on the basis of baseline water quality (this data is described in detail below), distance from tarmac roads, numbers of known users, and geographic region, and then randomly assigned (using a computer random number generator) to determine the order of in which protection would occur. Table 1 presents the baseline summary statistics across the treatment and comparison groups as of late 2005 (after two rounds of protection).

Several springs were unexpectedly found to be unsuitable for protection after the baseline data collection and randomization had already occurred, when more detailed technical studies were undertaken. These springs, which are found in both the treatment and comparison groups, were dropped from the sample, leaving 184 springs in the viable sample. Identification of the seasonal springs should not be related to treatment assignment: when the NGO was first informed that some springs were seasonally dry, all 200 sample springs were re-visited to confirm their suitability for protection. Comparisons across the treatment and comparison groups are very similar to those presented in Table 1 if attention is restricted to the sample of 184 springs where protection is viable (results not shown).

A representative sample of households that regularly use each sample spring was also determined at baseline. Survey enumerators visited each spring to interview spring users, asking their names as well as the names and residential locations of other households that use the spring. Enumerators then also elicited information on which households are known to use the spring from a convenience sample of three to four households that lived very near the spring. Households that were listed at least twice among all interviewed subjects were designated as spring users. Seven to eight households per spring were then randomly selected (using a computer random number generator) from among this spring user list for the household sample. The total number of household spring users varied fairly widely across springs, from eight to 59 with a mean of 31. Over 98% of this spring users sample was later found to actually use the spring at least sometimes during subsequent household surveys, attesting to the validity of the methods used to identify baseline spring users. The spring non-user households were nonetheless retained in the sample throughout the analysis.

The spring user households are largely representative of all households living near the springs. In a February 2007 census of all households living within approximately a 10 minute walk of seven sample springs, we found that 92% of these nearby households had been included on our original spring users list. The spring user list households may be less representative for households living farther than a 10 minutes walk away from sample springs.

Baseline water data was then collected at all 200 sample springs and a survey of local environmental contamination was completed at each spring (January-October 2004), including information on potential sources of contamination (e.g., latrines, graves), vegetation surrounding the spring, slope of the land, and spring maintenance conditions. Water quality in household drinking water storage containers was also tested, as was household survey data on demographic characteristics, health, anthropometrics, and water use choices. The survey is described below.

To address concerns about seasonal variation in water quality and health outcomes, all springs were randomly assigned (after being first stratified both geographically and by spring treatment group) to an activity "wave," and all data collection and spring protection activities were conducted by wave. The regression analysis uses district-wave fixed effects throughout to control for any seasonal variation in local water quality and disease burden.

The NGO proceeded with community mobilization meetings after baseline data collection and assignment to program groups, and then contracted local masons to carry out spring protection at the treatment springs. The NGO held community meetings during which community permission was obtained for the project, and at which permission was received from the spring landowner to protect the spring (in the two cases where the landowner did not grant such permission, springs were retained in the sample, so results can be interpreted as intention-to-treat estimates). The NGO requested that each community raise a modest initial contribution of 10% of the cost of spring protection, collected mainly in the form of manual labor and construction materials (e.g., sand and bricks). The total cost of spring protection, including these supplies and estimated labor costs, ranges between US$830 and

US$1070, depending on the type of construction, which is mainly a function of spring size and soil conditions. The spring was protected after the community raised the initial contribution, and this was successful at all treatment springs. A committee of spring users responsible for raising the community contribution and for maintaining the spring was also selected by community members attending the initial meeting. Construction quality was monitored by the NGO, and the mason was responsible for repairing any defects during the first three months after protection, after which the protected spring was "handed over" to the community as their property.

A first follow-up round of water quality testing at the spring and in homes, spring environment surveys, and household surveys were completed in both treatment and comparison spring communities three to four months after the first round of spring protection, in April through August 2005. In this survey, water quality data was not collected at nine springs due to logistical issues. Surveys were administered at 1263 of the 1389 households with baseline survey data.

The second round of spring protection was performed in August-November 2005, and the second follow-up survey round was collected in August-November 2006. In this survey, water quality data was collected at all springs but one. There are a total of 1105 households with all three rounds of spring water and household survey data.

3.2 Data collection procedures

The data collection strategy was designed to evaluate the impacts of spring protection on source water quality, home water quality, and child health (diarrhea incidence) and nutrition (anthropometrics). We also collected information on water source choices and health behaviors.

3.2.1 Water quality data

Water samples were collected from both springs and households in sterile bottles by field staff trained in aseptic sampling techniques.[7] Samples were then packed in coolers with ice and transported to water testing laboratory sites for analysis that same day. The labs use Colilert, a method which provides an easy-to-use, error-resistant test for *E. coli*, an indicator bacteria that is present in fecal matter.[8, 9] Continuous, quantitative measures of fecal contamination are available after 18-24 hours of incubation. Quality control procedures used to ensure the validity of the water testing procedures included the use of weekly positive controls, negative controls and duplicate samples (blind to the analyst), as well as monthly inter-laboratory controls.

As we discuss below, there appears to be substantial mean reversion in the spring water quality measurements. This suggests that multiple samples from a given source should ideally be tested to estimate "field sampling variability" and allow for this variability it to be appropriately modeled and accounted for statistically. We do not yet have such data and, to our knowledge, neither do the existing studies of water contamination between the source and home. Without such data, estimated correlations between spring and household water quality using cross-sectional observational data could suffer from some attenuation bias towards zero due to measurement error, leading the analyst to incorrectly conclude that there is more recontamination between water source

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[7] At springs, the protocol is as follows: a 250 ml bottle's cap is removed aseptically and not touched by hands during the taking of samples. Samples are taken from the middle of standing water and the bottle is dragged through the water so that sample is taken from several locations. About one inch of space is left at the top of the bottle when full. The cap is replaced aseptically. In homes, the protocol is similar. Following informed consent procedures, respondents are asked to bring a sample from their main drinking water storage container (usually a ceramic pot). The water is poured into a sterile 250 ml. bottle using a household's own dipper (often a plastic cup) and resulting estimates of contamination reflect conditions in the household's own water storage container and dipper.

[8] The Colilert method has been accepted by the U.S. Environmental Protection Agency (EPA) for both drinking water and waste water analysis. This was one of the first uses of this method in Kenya. Our laboratory standard operating procedures were adapted from the EPA Colilert Quantitray 2000 Standard Operating Procedures.

[9] There is currently no consensus microbial indicator for tropical and subtropical climates (where bacteria may live longer in the environment) . However, it is common to use *E. coli* as a means of quantifying microbacteriological water contamination in semi-arid regions like our study site. The bacteria *E. coli* is not itself necessarily a pathogen, but testing for specific pathogens is costly and can be difficult. Dose-response functions for *E. coli* have been estimated for gastroenteritis following swimming in fresh waters (Kay *et al*. 1994), but such functions may be highly-location specific because the particular pathogens present in fecal matter vary by location and over time.

and the home than there is in reality. The use of an instrumental variable (IV) approach, where source water quality is instrumented with assignment to spring protection, can address this issue as well as the problem of omitted variable bias (confounding) more generally. We find below that this econometric approach increases the estimated extent to which improved source water quality translates into home water quality gains.[10]

3.2.3 Household survey data

A household survey was administered to a representative sample of spring user households at all sample springs prior to the intervention, and again following each round of spring protection.[11] The target survey respondent was the mother of the youngest child living in the home compound (where the extended family often resides together) or another woman of child-bearing age, if the mother of the youngest child was not available. The respondent is asked about the health of all children under age five living in the compound, including recent diarrhea and dysentery (blood in stool) incidence.

The household survey instrument also gathered baseline information about hygiene behaviors and latrine use. Data on the frequency of water boiling, home water chlorination and water collection choices was collected. Respondents were also asked to give their opinion on ways to prevent diarrhea; they were not given options to choose from, and were prompted three times and their responses recorded. This information was then used to construct a “diarrhea prevention knowledge score” at baseline, namely, the number of correct responses provided by the respondent, from the choices: “boil drinking water”, “eat clean/protected/washed food”, “drink only clean water”, “use latrine”, “cook food fully”, “do not eat spoiled food”, “wash hands”, “have good hygiene”,

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[10] There are other potential sources of measurement error. First, Colilert generates a “most probable number” of *E. coli* coliform forming units per 100 ml in a given sample, with a known 95% confidence interval. Second, samples that are held for more than six hours prior to incubation may be vulnerable to some bacterial re-growth/death making the tested samples less representative of the original source.

[11] We identified households that were potential spring users by asking people who came to collect water at the springs to tell us the names of people that they thought used the springs. We also asked people living near the springs to provide such a list. If households were mentioned by two sources, we considered them spring users. A random sample of these people were then selected to be in our sample. As we discuss in greater detail, this procedure generated a sample of households that used the springs for varying amounts of water in practice.

“medication”, “clean dishes/utensils” or “other valid response”.[12] Survey respondents on average volunteered two to three such correct preventative activities, with 47% volunteering either boiling water or practicing good hygiene at baseline.

The definition of diarrhea asked of respondents in the survey is “three or more loose or watery stools in a 24 hour period,” which has been used in related studies (see Aziz *et al.* 1990 and Huttly *et al.* 1987). The questionnaire does not attempt to differentiate between acute diarrhea (an episode lasting less than 14 days) and persistent diarrhea (more than 14 days), but differentiates between dysentery and diarrhea by asking whether blood was present in the stool.

Survey enumerators used a board and tape measure to measure the height of children older than two years of age, and digital bathroom-type scales for weight. The height of children under age two was measured as their recumbent length using a pediatric measuring board, and enumerators used a digital infant scale to measure their weight.

We focus below on reported diarrhea in the past week as well as weight and height of children under three years of age as the main health and nutrition outcomes. To address concerns about measurement error in the health data (which may arise because of respondent uncertainty about child age or due to imperfect matching of children across rounds in the household roster, for example), we define a “severe” outlier as being more than three times the interquartile range beyond the 25th or 75th percentile in our data for child height. This eliminates 61 child-observations from the sample, out of 3655 total weight observations (and 5537 diarrhea observations and 3795 height observations) for children under age three for whom we have data at least two household survey rounds. We restrict our attention to children under age three at baseline because of concerns about increasingly misreported age data as children get older.

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[12] We reviewed all responses other than those listed here and categorized them as valid or invalid. The major additional correct responses that were not included on the original survey list were “solar water disinfection”, “breastfeeding”, and some variant of “use compost pit/keep compound clean”.

3.3 Attrition

We successfully followed up 90% of the baseline household sample between the initial round and the first follow-up survey round. Another ten percent of the sample appears to have been lost between the second and third rounds of data collection. Attrition is not significantly related to spring protection assignment: the coefficient estimate on the treatment indicator is only 0.01 (standard error 0.02) in a regression of the attrition indicator on treatment assignment, implying that treatment households are only one percentage point more likely to be lost across survey rounds, and the result is robust to including further explanatory variables as controls (regression not shown).

The baseline characteristics of the households that we lose over time are typically statistically indistinguishable from those that remain in the sample. Economically better-off households do not appear any more likely to be lost from the sample; iron roofing in the household compound, an asset ownership measure in our survey, is not significantly related to attrition. The same weak relationship holds between attrition and baseline household water quality and hygiene knowledge. One partial exception is that households lost from the sample are slightly (5 percentage points, standard error 3 percentage points) less likely to have soap in the home at baseline, but overall, sample attrition bias appears likely to be small.

4 Baseline descriptive statistics

Table 1 presents baseline summary statistics for springs (Panel A), households (Panel B) and children under age three (Panel C). For completeness, we report baseline statistics for all springs and households for which data was collected prior to randomization into treatment groups even if they are later not included in the regression analysis because the spring was later determined unsuitable for protection, although results are very similar with the main analysis sample.

The water quality measure, *E. coli* MPN CFU/100 ml, takes on values from 1 to 2419[13]. We categorize water samples with *E. coli* CFU/100 ml < 1 as "high quality" water. For reference, the U.S. EPA and WHO standard for clean drinking water is zero *E. coli* CFU/100 ml and the EPA standard for swimming/recreational waters is *E. coli* CFU/100 ml < 100. We call water between these two standards "moderate quality" water. We also create a category of "high or moderate quality" water (with *E. coli* CFU/100 ml < 100) because we rarely observe high quality samples in our data. This is not surprising as the water is neither in a sterile environment nor has residual chlorine as treated drinking water does. We divide the remaining values of *E. coli* CFU/100 ml > 100 into two categories, "poor quality" water (values between 100 and 1000) and "very poor quality" water (greater than 1000).[14]

There is no statistically significant difference between the water quality at treatment versus comparison springs at baseline (Table 1, Panel A), which implies that the randomization (using a computer random number generator) created broadly comparable program groups.[15] The spring water in our sample is of moderate quality on average. Only about 5 to 6% of samples from unprotected springs would meet the stringent U.S. EPA drinking water standards, while over a third of samples are poor or very poor quality.[16]

Summary statistics for household water quality are presented next (Table 1, Panel B). Home water is somewhat more likely to be of high quality prior to spring protection in the treatment group

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[13] In the laboratory test results, the E. *coli* MPN CFU can take values from <1 to >2419. We currently ignore the censoring of the data and treat values of <1 as equal to one and values of >2419 as equal to 2419.

[14] The value of 1000 *E. coli* CFU/100 ml was chosen as a threshold because observational studies suggest that diarrhea incidence can increase rapidly above this level in other less developed country contexts. [CITE]

[15] In practice, a substantial fraction of water samples were held for longer than six hours, the recommended holding time limit of the U.S. EPA, but we have confirmed that baseline water quality measures are balanced across treatment and comparison groups when attention is restricted to those water samples that were incubated within six hours of collection, yielding the most reliable estimates (results not shown).

[16] Previous research in Nigeria shows that unprotected spring water is generally of higher quality than water from ponds or rivers, but that it is vulnerable to spikes in contamination at the transition between rainy and dry seasons. Our data collection stretched over several months both at baseline and at follow-up (Figure 2), and data collection activities were stratified across geographic regions in data collection waves. To account for potential seasonal variation in water quality, we include seasonal fixed effects in all regression analysis.

(and the difference between treatment and comparison group means is significant at 95% confidence), but there is no statistically significant difference in the proportion of samples where water is of moderate or poor quality.

At baseline, household water quality tends to be better than spring water quality on average. In the full sample, the average difference in log *E. coli* between spring and household water is 0.57 (s.e. 0.15, n = 1193 households; results not shown). This likely occurs for at least two reasons: first, many households collect water from sources other than the sample springs and these may be less contaminated on average, and second, some households use point of use (POU) treatments to improve home water quality. Only a bit more than one half of the household sample gets all their drinking water from the local sample spring at baseline and overall respondents make about 70% of all their water collection trips to their sample spring. In a cross-sectional regression, households that collect all their drinking water from their sample spring have significantly more contaminated home water (not shown), consistent with the view that unprotected springs are a relatively contaminated source, although the extent of contamination is likely to vary by season.

Some households report taking additional measures to treat their home water. For instance, about 25% of households report boiling their drinking water at baseline. We also collected data on chlorination in the first follow-up survey: 28% of households reported chlorinating their water at least once in the last six months.[17, 18] Yet the correlations between self reported household water boiling or chlorination with observed household water contamination are very low, raising questions about the accuracy of these self-reports. Social desirability bias is a leading concern. One potential explanation for the low correlation is that water is sometimes boiled or treated immediately before

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[17] These chlorination levels are almost certainly higher than would usually be observed because the Government of Kenya distributed free chlorine tablets in part of our study region following a 2005 cholera outbreak. In future survey rounds, we will test for residual chlorine in home water for a more reliable measure of ongoing chlorine use.

[18] Solar disinfection is also occasionally practiced in this area, but we did not collect data on this at baseline.

use (e.g., when making tea), and thus the water samples we tested could overstate contamination at the time of actual consumption.

Household water samples are also held for a shorter length of time than spring water samples, on average.[19] However, this does not explain the observed differences between household and spring water quality: the difference between mean spring and household water quality (measured by ln *E. coli* MPN) is significantly different than zero even when we restrict attention to those water samples held for less than six hours before incubation (the difference in means is 0.56, s.e. 0.08, n = 737).

There are few statistically significant differences in household, respondent and child characteristics across the treatment and comparison groups (Table 1, Panels B and C), further evidence that the randomization was successful at creating balanced program groups. Average mother's education attainment is equivalent to less than primary school completion, at about six years (primary school goes through grade 8 in Kenya). One-third of respondents do not have a building with an iron roof in their home compound, where in this area iron roofing is an indicator of relative wealth. There are about four children under age 12 residing in each respondent's compound on average. Water and sanitation access is fairly high compared to many other rural settings in less developed countries as about 85% of households report having a latrine, and the average walking distance (one-way) to the closest local water source is only approximately 10 minutes.

There are similarly no significant differences across treatment and comparison groups in terms of the respondents' "diarrhea prevention knowledge" score, water boiling behavior, or self-reported understanding of the links between water quality and diarrhea. There are also no differences between compound cleanliness and soap ownership. However, 90% of treatment group households and 93% of comparison households cover their drinking water containers, and this difference is significant at 95% confidence. It is unclear what accounts for this difference, but we conclude that it

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[19] This is likely because spring water samples are often collected toward the beginning of a field day, while household water samples are collected throughout the day and are more likely to be collected at the end of the day.

is unlikely to be an important indicator of home water quality differences because there is no difference in *ln E. Coli* across the groups.

We report summary statistics for the subset of children under age three for whom we have both baseline and follow-up survey data in Table 1, Panel C. Children are comparable across treatment and comparison groups in terms of height and weight, our preferred nutritional status measures. For example, a fairly high 21% of children in the comparison group had diarrhea in the past week at baseline, as did 23% in the treatment group. There are similarly no statistically significant differences in other non-diarrheal illnesses (e.g., fever, cough) or in breastfeeding across the two groups (results not reported).

5 Spring protection impacts on source water quality

5.1 Estimation strategy

Equation 1 illustrates an intention-to-treat (ITT) estimator using spring-level data. Linear regression is employed both when the outcome is continuous – such as the natural log of the *E. coli* MPN measure – and when the dependent variable is an indicator variable (such as for high quality water, *E. coli* MPN < 1, for example), although results are similar using probit analysis in the latter case (results not shown).

$$W_{it}^{SP} = \alpha_{dt} + \beta_1 T_{it} + X_i^{SP\prime}\beta_2 + (T_{it} * X_i^{SP})'\beta_3 + \varepsilon_{it}. \qquad (1)$$

W_{it}^{SP} is the water quality measure at spring i at time t ($t \in \{0, 1, 2\}$ for the three survey rounds) and X_i^{SP} are baseline spring and community characteristics (e.g., initial level of spring water contamination). The variable T_{it} is a treatment indicator that takes on a value of one after spring protection has occurred, and this is the case for treatment group 1 in both follow-up survey rounds, and for treatment group 2 only in the second follow-up survey round. ε_{it} is the standard white noise disturbance term.[20] Randomized assignment implies that the coefficient estimate of β_1 is an unbiased estimate of the reduced-form ITT effect of spring protection. In some specifications we explore the possibility of differential effects as a function of spring-level baseline characteristics, captured in the vector of coefficients β_3. District-wave (season) fixed effects α_{dt} are also included in the regression analysis to control for any time-varying factors that could affect all treatment groups.

5.2 Spring water quality results

We report difference-in-differences estimates of the impact of spring protection on source water quality, first for the natural log of *E. coli* MPN (Table 2, Panels A and C) and then for an indicator of whether water is high quality (*E. coli* < 1 MPN, Panels B and D), as the first step in tracing out the impacts of the intervention on water at springs and in homes, and ultimately on child health. The top two panels of the table report results for the first round of treatment springs (protected in early 2005) versus other springs, using the baseline data and the first follow-up survey, while the bottom two panels of the table report results comparing both treatment groups together (both those protected in early 2005 and in late 2005) to the other springs, using the baseline and the second follow-up survey.

Spring protection dramatically reduces contamination of source water with the fecal indicator bacteria *E. Coli*. Using both rounds of data indicates that the average reduction in ln. *E. coli* is between 72-77% (Table 2, Panels A and C), with nearly identical results across treatment rounds.. Figure 3 is a non-parametric (lowess) representation of the data that shows some gains are

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[20] Assignment to treatment may also be used as an instrumental variable for actual treatment (spring protection) status, to estimate an average treatment effect on the treated (TOT) using a two-stage procedure (Angrist, Imbens, and Rubin 1996). In practice, in only 10 springs (of 200) did assignment to treatment differ from actual treatment (because landowners declined to allow the NGO to protect a spring on their land or because the government independently protected springs that were in our comparison group, for example) and thus TOT regressions yield results very similar to the ITT estimates we focus on.

experienced at nearly all treatment springs, with the springs most contaminated at baseline experiencing the largest average impacts.[21]

It is difficult to predict how these reductions in source water contamination translate into health outcomes, since the relationship between water quality and health is not necessarily log-linear. A more natural measure of improvement in drinking water is to focus on whether source water meets the stringent EPA drinking water standard, what we call high quality water. We find that spring protection does increase the probability of high quality source water, but that relatively few springs achieve this standard even after protection (Table 2, panels B and D). The first round of follow-up data indicates that protection increases the probability of meeting EPA/WHO standards by 11 percentage points (nearly significant at 90% confidence), while in the second follow-up round protection increases the probability of meeting the standard by 18 percentage points (statistically significant at 99% confidence), but up to only 29% of sources meet this standard in the treatment group after protection.

These estimated spring protection treatment effects on source water quality are robust to the inclusion of controls for baseline contamination and district-wave (season) fixed effects (Table 3, regressions 1 and 2). Regression analysis confirms the finding that spring protection leads to a significantly greater percentage reduction in water contamination when initial contamination was highest (regressions 3 and 4). We also test for differential treatment effects by baseline household survey respondent hygiene knowledge (the average among users of that spring) and as a function of average local sanitation (latrine) coverage at baseline, as well as by baseline household assets as proxied by iron roof density (regression 4), but these interaction terms are not statistically significant.

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[21] The change in ln(*E. coli*) is actually positive for the springs with the highest baseline water quality, again suggesting there is some mean reversion in spring water quality measures between survey rounds.

6 Estimating home water quality impacts when water source choice is possible

We first develop a simple model of water source choice in the presence of travel costs and then derive implications for the estimation of home water quality impacts and of household valuation of less contaminated water.

6.1 A travel cost of model of household water source choice

Estimating the impact of spring protection on water quality in the home is complicated by the possibility that households will change their behavior in response to source water quality changes. The two most immediate choices households face are the choice of a water source, and the choice of whether or not to employ point-of-use technologies (e.g., boiling or chlorination). We discuss each of these in turn below, but focus mainly on the choice of water source. The fact that households in our study area often have access to multiple water sources, varying in the quality dimension as well as in terms of walking distance from the home, allows us to value improvements in water quality using a travel cost approach (Freeman 2003).

Imagine first that households are located along a line between two water sources, the spring (denoted with letter s) and the alternative source (a), which could be a borehole well, a stream, or another non-sample spring. The round-trip distance (in minutes walking) from the home to the spring for the household is D^s, while the round-trip distance to the alternative source is D^a. The difference in walking times across the sample spring and alternative source is $D \equiv D^s - D^a$, which we call the walking "distance gap" between the two sources. The distance gap can take on positive or negative values, where negative values denote households that live closer to the sample spring than to the alternative source. The distance gap for a household i is denoted D_i. For now we assume that households are homogeneous along all dimensions except for the distance gap, but relax this below.

In choosing a water source, households trade off the cost (the distance they need to walk to the source) versus the benefits (improved household water quality, which affects their health). The opportunity cost of time – per minute in this case – is denoted $C > 0$. This is a function of the local market wage, and we assume this is constant across all households. Thus the extra cost household i bears to make one additional water trip to the spring (rather than to the alternative source) is CD_i, where again this cost can be positive or negative.

The water contamination level (measured as ln (*E. coli* MPN)) for water source j, $j \in \{s, a\}$, is denoted $W_j > 0$, where higher values denote more contamination and thus lower quality. The function relating water quality to household members' health is denoted $V(W_j)$, where $V' < 0$. There may be non-health benefits to getting water from a low contamination water source (for instance, the improved appearance of a protected source) that are also captured in V.

There are two time periods to consider, pre-treatment (pre-spring protection) and post-treatment. The water contamination level in the sample spring pre-treatment is denoted W_s and post-treatment is W_s^T (where "T" denotes treatment). Empirically, the experimental spring protection intervention led water contamination levels to fall, $W_s^T < W_s$. We assume the water contamination level in the alternative source, W_a, is constant over time.[22]

Household utility from a single water collection trip to source $j \in \{s, a\}$ can be represented as the linear function $U_j = V(W_j) - CD^j$. Household i chooses the sample spring over the alternative source if the benefits of higher water quality outweigh travel costs, namely when $\{V(W_s) - V(W_a)\} - CD_i \geq 0$. More generally, in a richer context with multiple alternative water sources like our empirical setting, the household chooses the source that maximizes utility over all options in the choice set.

Consider first the simplest case. In the pre-treatment period, household i chooses spring water if $\{V(W_s) - V(W_a)\} - CD_i \geq 0$, or equivalently if the distance gap is sufficiently small such that $D_i \leq \{V(W_s) - V(W_a)\}/C \equiv D^*$, where D^* can take on positive or negative values. Thus, in this model

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[22] We do not yet have data on the water quality of alternative local sources, but are currently in the process of collecting this data and will incorporate these data into future analysis.

households with distance gap up to some threshold level use spring water, while those farther away choose the alternative source.

After spring protection, spring water quality improves relative to the alternative water source, and households choose spring water if $D \leq \{V(W_s^T) - V(W_a)\}/C \equiv D^{**}$, where $D^{**} > D^*$ since spring water is now less contaminated than before ($W_s^T < W_s$). Thus households living at a greater distance from the spring increasingly choose spring water.

Endogenous source choice has implications for the quality of drinking water chosen by households. For households that were spring water users in the pre-treatment period ($D_i \leq D^*$, corresponding to the baseline "sole-source" spring users in our data), their home water quality is unambiguously better after treatment since they still rely exclusively on the spring for drinking water and its quality has improved after protection.

The story is more complicated for households that initially used the alternative source but switched to using the spring after treatment ($D_i \in (D^*, D^{**}]$), the group that corresponds most closely to the multi-source users in our data. For these households, the quality of drinking water in the home could theoretically increase or decrease after treatment.[23] To illustrate, imagine the case in which an improvement in water quality at the spring induces a household to switch from a distant but high quality alternative source (say, a new borehole well) to the closer but relatively lower water quality spring. This could be optimal because households are trading off water quality against time spent walking to collect water. In this case, even if the water quality chosen by the household deteriorates somewhat since they increasingly use the now-protected spring, the household is still made better off by spring protection in the sense that household members benefit from time savings. The theoretical prediction on the change in home water quality for these multi-source user households remains

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[23] For households with an even larger distance gap, $D_i > D^{**}$, there is no change in home water quality since they continue to use the alternative water source just as before, and the alternative source's water contamination level does not change (by assumption). This is not an empirically relevant case for us since even households in our data with large distance gaps relied at least partially on the sample spring for drinking water at baseline. This is due to the initial selection of sample households as at least occasional "spring users".

ambiguous, in contrast to the sharp theoretical prediction of improved home water quality for the sole-source users who use the sample spring throughout.

It is conceptually straightforward to calculate households' valuation of the water quality improvement caused by spring protection in this simple model, focusing on those households on the margin between using the spring and using the alternative source. After the water quality improvement at the spring ($W_s^T < W_s$), yielding household utility benefits $\{V(W_s^T) - V(W_s)\}$, travel costs must increase by $C(D^{**} - D^*)$ to restore households to indifference between using the two sources. The greater travel cost households are willing to incur is thus a direct revealed preference measure of the value of improved water quality. Conceptually at least, this model could also be used to estimate household valuation for avoided illness as a result of consuming less contaminated water, though we are unable to make such estimates at this time due to the lack of statistically significant estimated health impacts of the intervention (see section 7).

Other factors can be added to increase realism and bring the model closer to the data. First, there may be more then two alternative sources, and the water contamination levels of each of these springs and alternative sources vary. Second, households make multiple trips to each spring, and each trip choice is affected by un-modeled factors including the weather, the queue at the water source, the direction they are walking for another task (i.e., walking to the market to buy food) or individuals' mood on a given day. These factors enter the decision problem through the idiosyncratic error term. Incorporating this i.i.d. error term e_{jt}, which can conveniently be modeled as type I extreme value, the utility of a water collection trip to source j at time t is: $U_{jt} = V(W_{jt}) - CD^j + e_{jt}$, and the spring is chosen by household i for trip t if this maximizes household utility over all possible sources j. This yields the usual logit form for choice probabilities. In practice we estimate a conditional logit model (following McFadden 1974).[24]

Households also face the choice of whether or not to adopt a POU water technology, such as water boiling or chlorination prior to water consumption. Consider the case of chlorination, for concreteness. There are several dimensions of the cost of adopting chlorination in the home, which we denote C_P. These include the purchase price of the chlorine, the time needed to purchase the chlorine and put it in the drinking water container, any psychic costs from learning how to use the product, or costs due to the fact that chlorinated water is not as tasty as untreated water. Offsetting these costs are benefits in the form of reduced water contamination. We model this as a reduction down to contamination level W_P. In this case chlorination and spring protection are substitutes (there are also scenarios under which they could be complements[25]), and thus improvements in water quality due to spring protection would, if anything, reduce point-of-use technology take-up.

The household chooses to employ the point-of-use technology when the water quality gains of adoption outweigh the costs. Empirically, as we discuss below, the take-up of point-of-use technologies is low in our study area, and we do not see large shifts in their use after spring protection. This is consistent with the view that the costs – pecuniary or otherwise – of point-of-use technologies are currently relatively large in our study area.

Another extension of the framework incorporates a role for hygiene practices and access to sanitation. Influential research argues that water quality improvements alone are insufficient in improving health in the absence of complementary hygiene and sanitation investments that reduce recontamination in storage and transport (Esrey 1996). This can be incorporated into our framework

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[24] In future work, when we have additional data on the water contamination of alternative local water sources, we plan to utilize the richer mixed logit framework, which will allow us to estimate the heterogeneity in household preferences for cleaner water.

[25] For instance, if chlorination reduced water contamination by some fixed amount ΔW regardless of the starting contamination level, and the health benefits function $V(W)$ were convex and decreasing, then improved source water quality and point-of-use technologies could be complements and spring protection could actually boost demand for point-of-use chlorination technologies.

by making water quality from source j, W_j, a function of both protection ("treatment", $T_j \in \{0,1\}$) as well as the local hygiene and sanitation environment, denoted H_i, where improved hygiene and sanitation is associated with an increase in H_i. Imagine that this variable is fixed for household i (in a richer model investments in hygiene knowledge and sanitation could be endogenized along the lines of the point-of-use technology discussed above). H_i can concretely be thought of as the recontamination level of water from source j to the home.

The level of water recontamination in the absence of spring protection, in a setting with minimal hygiene and sanitation, is denoted W_j^*. Formally, let $W_j = W_j^* - \phi(T_j, H_i)$, where $\phi_1 > 0$ (spring protection reduces water contamination at the source) and $\phi_2 > 0$ (better hygiene and sanitation in household i reduces recontamination during transport and storage). The sign of the cross-partial derivate, ϕ_{12}, determines whether spring protection and hygiene/sanitation are substitutes or complements in reducing water contamination.[26] Below we estimate this interaction effect of spring protection with measures of household hygiene knowledge and sanitation access.

6.2 Estimating spring protection impacts on water source choice and behavior

We estimate an equation analogous to equation 1 but using household level data in order to gauge the impact of spring protection on household behaviors – including water source choice, self-reported water boiling, self-reported water chlorination, diarrhea prevention knowledge, and number of trips made to collect water in the past week, a measure of water quantity used – as well as impacts on home water quality. Once again, econometric identification relies on the randomized program design.

We consider the theoretical predictions derived above by splitting the data into two subsamples, the initial sole-source users (those households who only used the sample spring at baseline) and multi-source users (those households who also used other sources for water at

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[26] Spring protection and hygiene/sanitation could also be substitutes or complements even if the ϕ function is linearly separable, as long as V is convex.

baseline). The predictions are, first, that use of the protected spring should increase among initially multi-source user households while sole-source user households continue to exclusively use the spring, and second, that home water quality improvements among sole-source user households should be at least as large as gains observed for multi-source user households. We are also interested in testing Esrey's (1996) hypothesis that sanitation and hygiene are complements with source water quality improvements.

We control for baseline household characteristics in some specifications including household sanitation access, the respondent's diarrhea prevention knowledge score, an indicator for whether a household has an iron roof (a proxy for wealth), the respondent's years of education, and the number of children under age 12 in the compound at baseline, in addition to district-wave (season) fixed effects. Regression error terms are clustered at the spring level in these household-level regressions. Randomization of the intervention at the level of the spring community means that the households using the same spring at baseline are not independent units of study, and outcomes among these households may be correlated. Not only do these households share a common water source, but they may be related by kinship ties, and may share the use of the same latrines and alternative water sources. This reduces the power of statistical tests relative to what would be possible if a source water quality intervention were randomized at the household level.

We also test the hypothesis that source water quality improvements are more valuable in the presence of improved household sanitation access and/better or hygiene knowledge (as argued by Esrey 1996) by interacting the spring protection treatment indicator variable with these variables. We also allow for differential treatment effects by self-reported water boiling at baseline, the leading point-of-use water treatment strategy in our study area. Households that boil their home water could reduce contamination levels, weakening the link between source and home water quality.

Finally, we also estimate the extent to which improvements in source water quality translate into to improved household water quality, where the equation of interest is:

$$W_{ijt}^{HH} = \alpha_{dt} + b_1 W_{it}^{SP} + X_{ij}^{HH\prime} b_2 + v_i + e_{ijt}. \qquad (2)$$

The dependent variable is water quality (measured in units of ln (*E. coli* MPN)) in household *j* at spring *i* in time period *t*, and the independent variables are the analogous spring water quality measure and the vector of baseline household characteristics described above. As before, we control for baseline treatment group assignment as well as district-time effects. The common spring-level error component is captured by v_i and e_{ijt} is a standard white noise error term. We focus this analysis on the sole-source user households, where the model predicts the greatest home water quality gains.

Random assignment of springs to protection implies that we can avoid both omitted variable bias (confounding) and also reduce attenuation bias due to measurement error by estimating b_1 in an instrumental variables framework. In particular, assignment to spring protection treatment multiplied by an indicator variable for the "After treatment" time periods is the instrument for spring water quality. The first-stage regression equation is nearly identical to equation 1 above, using data from all three time periods (both $t=0$ "Before treatment," $t=1$ "After treatment (follow-up survey 1)," and $t=2$ "After treatment (follow-up survey 2)"). The treatment assignment indicators and the time effects are included as explanatory variables in both the first and second stage regressions. This IV approach provides an analytically attractive means of estimating the degree of water contamination between source and home, especially among the sole source user households who almost exclusively use the sample spring for drinking water in both periods.

6.3 Household water choice and home water quality results

We first consider impacts on water collection and source choice (e.g., the number of trips made to collect water from the household's primary source), water transportation and storage behaviors (e.g., reported water boiling and water chlorination), and complementary sanitation and hygiene behaviors (e.g., diarrhea prevention knowledge score at follow-up). We report results for the full sample of households, and for sole source users and multi-source users separately, given the interesting theoretical distinctions across these two groups of households.

The main behavioral change that resulted from spring protection is an increase in the use of the protected springs for drinking water, while other behavioral changes appear to be minor. Assignment to spring protection treatment is strongly positively correlated with use of the sample spring for those households not previously using it: treated households are 21 percentage points more likely to use their sample spring as a source of drinking water if they used other sources at baseline (Table 4, Panel A). Sole source users already used the springs and so make few changes in spring use as a result of treatment. There are similarly large impacts on the fraction of water collection trips made to the sample spring after protection for multi-source users. Underlying this increase in use of protected springs were increasingly positive perceptions about the quality of drinking water from protected springs: respondents at treated springs were 24 percentage points more likely to believe the water is "very clean" at the source during the rainy season, and these effects are similar for both sole-source and multi-source user households.

There were small statistically significant effects of spring protection on the average distance households walked to their main drinking water source (recall that the average length was about 8 minutes one-way or 16 minutes round-trip). There was no overall effect on the number of trips made to water sources in the past week. Similarly, there are no significant changes in most water transportation and storage behaviors, although some small shifts in self-reported water boiling at home (Table 4, Panel B). Households at treated springs are somewhat more likely to boil water (suggesting that this is complementary rather than a substitute for spring protection), but it is unclear to what extent this is the result of reporting bias. There is also no evidence of changes in self-reported diarrhea prevention knowledge nor in other household hygiene measures (Panel C).

Survey enumerators collected additional information on the extent of maintenance at the spring, and find that protected springs have significantly "clearer" water, better fencing, and less fecal matter, animals and brush in the vicinity (Table 4, Panel D). In contrast, there is no effect on the observed yield of water at the spring, confirming that spring protection allows us to isolate water quality effects in the analysis rather than water quantity effects.

We next turn to estimating the effect of spring protection on water quality in the home, reporting difference-in-differences estimates in a manner analogous to the spring-level analysis. We focus on the natural log of *E. Coli* as a measure of contamination, and look separately at treatment effects for the full sample of households (Table 5, Panels A and B), for sole-source spring users who get all their water from the local spring (Panels C and D) and for multi-source users who collect water from several locations (Panels E and F). As in Table 2, we present estimated treatment effects for both follow-up survey rounds (2005 and 2006). In both cases, the average impact of spring protection on home water quality is far smaller than the impacts on source water quality. Using the 2006 data for the full sample of households, the average reduction in water contamination is only 26% (Table 5, Panel B), only about one-third the 77% reduction at the spring level (Table 2, Panel C) and not statistically significantly different from zero.

One theoretically plausible explanation for limited observed home water quality gains is the possibility of endogenous sorting of households among water sources springs in reaction to spring protection, which would dampen observed gains at home if some households switch to using closer but lower quality spring sources. The data bears out these model predictions. Among the sole-source spring users, spring protection impacts on home water quality are substantial, including 52% and 36% reductions in average home water contamination using the 2005 and 2006 data, respectively (Table 5, Panels C and D), while for multi-source users home water gains are essentially zero (Table 5, Panels E and F). This result for sole-source users is our first empirical indication that recontamination of water in transport and storage is not a major factor reducing home water quality in our setting, since if that were the case, we would expect large drops in water quality between source and home even for the sole-source spring users who use the same water source (the sample spring) throughout.

Similar results obtain for the full sample, and for the sole-source and multi-source users, when baseline household characteristics are included as explanatory variables in a regression framework (Table 6). Once again, the overall effect of spring protection on home water quality is moderate (regressions 1-3), with somewhat larger effects for the sole-source households than the multi-source users (regressions 2-3), though we cannot reject equal treatment effects for sole source and multi-source users in these specifications.

The analytical payoff from the multiple regression framework lies in allowing us to estimate treatment effects for households with different baseline characteristics. We find no evidence of differential treatment effects as a function of household sanitation, water boiling, diarrhea prevention knowledge, or distance to the water source (Table 6, regression 3). Households living in communities with greater latrine coverage do appear to have less contaminated water, but this is does not differentially affect the impact of the spring protection treatment. The fact that there are no differential effects as a function of pre-existing sanitation access or hygiene knowledge runs counter to claims common in the literature that source water quality improvements are most valuable when these complementary factors are also in place. Perhaps surprisingly, baseline mother's diarrhea prevention knowledge is also not significantly related to observed household water quality in any regression specification. One possible explanation is that these measures miss some important dimension of hygiene or sanitation access, but if so it is not immediately obvious what these are.

To more fully assess the extent of water recontamination in transit and storage, we next examine the relationship between spring water quality and home water quality. In the simplest linear regression of home water quality (in ln(*E. coli* MPN)) on spring water quality (in the same units), in a specification that effectively ignores the experimental project design, we estimate an elasticity of only 0.216 (Table 7, regression 1). With only these results in hand, a naïve conclusion would be that water recontamination in transport and storage prevents 80% of source water quality improvements from reaching the home, and thus that source water quality improvements like spring protection are largely ineffective at improving home water quality. Even when attention is restricted to sole-source spring user households, and thus the complication of endogenous sorting is largely avoided, this framework leads to a similar estimated elasticity of 0.227 (regression 2).

An instrumental variable approach that exploits the experimental variation in source water quality and also addresses possible attenuation bias due to water quality measurement error tells a different story for the sole-source users: the elasticity estimate rises dramatically to 0.659 (statistically significant at 95% confidence, Table 6, regression 3). In this subsample of households where endogenous water source choice is effectively eliminated, nearly two thirds of the source water quality gains at the source generated by spring protection are thus translated into home water quality gains.[27] A regression in first-differences suggests that nearly all source water quality gains make it to the home once time-invariant household characteristics are differenced out, but this coefficient is imprecisely estimated and we do not emphasize it (0.973, s.e. 0.637, not shown).

Taken together, this analysis is strong evidence against the claim that recontamination renders source water quality improvements useless in this setting. We conclude that the impacts of spring protection on household water quality are large and statistically significant for those households that mainly use the same water source throughout (the sole-source user households). The richness of our longitudinal household survey and water quality data, together with the experimental program design that generated exogenous variation in source water quality, allow us to reach very different conclusions than would be suggested by existing analyses using observational cross-sectional data.

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[27] Note that the instrumental variables regression cannot be interpreted in the same way for the multi-source users, precisely because these households respond to treatment by switching among sources with variable water quality.

7 Child health and nutrition impacts

We estimate the impact of spring protection on child health outcomes using child-level data (usually reported by the child's mother) as well as anthropometric data collected by survey enumerators in the household survey in equation 3:

$$Y_{ijt} = \alpha_i + \alpha_{dt} + \beta_1 T_{ijt} + X_{ij}'\beta_2 + (T_{ijt} * X_{ij})'\beta_3 + u_{ij} + \varepsilon_{ijt} \qquad (3)$$

where the dependent variables that we focus on are diarrhea in the past week, child weight and height. The coefficient estimate on the variable indicating treatment in that time period captures the treatment effect, β_1. We also include child fixed effects in all regressions (α_i) and district-time effects (α_{dt}). We also consider separately the treatment effects for children living in sole-source user households versus multi-source user households, given the different home water quality impacts across these two groups.

Despite the home household water quality gains that we estimate, particularly in the sole-source user households, there are no statistically significant estimated treatment impacts on any of the child health or nutrition measures (Table 8). The signs on the coefficient estimates on the treatment term provides suggestive evidence that diarrhea may have fallen and weight improved slightly, but these effects are not statistically significant at traditional confidence levels. The weak results hold even focusing attention to the sole-source users (in regressions 2, 5 and 8, the coefficient estimate on the "Treatment (protection) indicator" term can be interpreted as effects for sole-source users). The lack of a statistically significant impact on reported diarrhea may not be surprising, in light of the fact that we measured this outcome only at three moments in time and it is notoriously difficult to measure accurately. But consolidated health gains should probably be more apparent with the anthropometric measures since the period between spring protection and the second follow-up survey was roughly a year and a half. When we allow for the possibility of stronger treatment effects in the second follow-up survey round (regressions 3, 6, 9), there is some suggestive evidence of increasing effects on weight over time, but none of these estimates are statistically significant. With alternative outcome measures (e.g., diarrhea plus fever or diarrhea in the past 24 hours), or alternative specification (e.g., including children up to age five) we similarly do not find any indication of statistically significant treatment effects.

Statistical precision is a concern, given the limited sample of infants and young children, however we do have sufficient statistical power to reject large spring protection impacts on health. The estimates in Table 8 allow us to reject reductions in diarrhea in the past week of greater than about forty percent both overall and among sole source users at 90% percent confidence. Among the group of sole source users – households who experienced quite large home water quality improvements – we can reject weight gains of greater than 0.72 kilograms with 90% confidence and height gains of only 0.53 centimeters (less than 1% of average baseline height) with 90% confidence.

While measurement error may explain the lack of statistically significant treatment effects for diarrhea, these results are also consistent with what might be found if the primary causes of diarrhea were water washed (arising because of insufficient water for washing and bathing) rather than water borne (transmitted via ingestion of contaminated water), or if there are important threshold effects relating drinking water quality and health. Certainly, spring protection could only be expected to address waterborne illness here, since we see empirically that there are no changes in the number of trips made to collect water as a result of treatment (Table 4, Panel A). In this area of Kenya, the reduction in diarrhea prevalence that could be expected from completely addressing waterborne illness is about 25% (confidence interval -40% to -5%) (Crump et al. 2005). This is the reduction observed in a cluster randomized control trial of point-of-use (POU) water treatment devices that resulted in 82% of treatment households with *E. coli* MPN <1, a far greater water quality improvement than we observe as a result of spring protection (where far fewer sole-source user households in the treatment group have *E. coli* MPN <1 after protection). Thus, impacts of spring protection should be expected to have smaller impacts on diarrhea prevalence than point-of-use water treatment. Of course, this does not imply that spring protection is necessarily less cost-effective than point-of-use water treatment: smaller reductions in diarrhea in a sufficiently large number of spring user households could still imply that spring protection is relatively more cost effective than in-home water treatment, at least in theory.

We will be collecting additional child health and nutrition data in future survey rounds to improve the statistical precision of this analysis, and thus still regard these conclusions about health impacts of the intervention as tentative.

8 A revealed preference estimate of household valuation of cleaner water

We next use the data on household water source choices to recover a revealed preference measure of household valuation of the water quality gains generated by spring protection. We focus on a conditional logit model consistent with the linear random utility framework developed in section 6.1 above. Given a set of characteristics X_{ijt} for individual i and spring j at time t – and here crucially the controls include both the protection status of the local sample spring and the walking time to each potential alternative water source – the probability that household i chooses source j from among the set of all potential water source alternatives $h \in H$ at time t can be represented as $P(y_{ijt} \mid x) = exp(x_{ijt}'\beta) / \{ \Sigma_h exp(x_{iht}'\beta)\}$.

This method allows for a travel cost approach to valuing the willingness to pay (WTP) for spring protection. The ratio of the coefficient estimate on the treatment (protection) indicator variable to the coefficient estimate on the walking time to a source delivers the value of spring protection in terms of minutes spent walking. By placing a value on individuals' time, we can back out a valuation of spring protection in monetary terms. Here we value time at US$1 (70 Kenya shillings) per day, which is at the lower end of agricultural wages in the study area, since collecting water is likely to be a job for relatively unskilled individuals in the household.

There is potentially substantial heterogeneity in both household's valuation of spring protection as well as in their time costs. We allow the coefficient on these two terms to vary as a function of households' baseline characteristics, and in particular as a function of the number of children of different ages in the household, by including interactions between these characteristics and both the treatment indicator and the walking distance term.

The conditional logit analysis yields a large, negative and statistically significant effect on the distance to water source (minutes walking) term, at -0.023 (standard error 0.0027, Table 9, regression 1) and a positive but not statistically significant effect on the treatment (protected) indicator term (0.084, standard error 0.116). Other terms in the regression indicate that wells tend to be preferred sources relative to the omitted category (non-program springs), and streams and rivers are less preferred sources, while there is no clear preference ordering overall among program springs, non-program springs, and boreholes.

The ratio of the two main coefficient estimates in this specification (taking into account that the walking time is one way) implies that spring protection is valued at 2*(0.084)/(0.023) = 7.2 minutes of walking time. This is a moderately large effect: if household members' time is valued at US$1 per day (or US$0.0021 per minute), and households make our sample average of 47 water collection trips per week, 52 weeks per year, the total average value to households from protection is (7.2 minutes)*(US$0.0021/minute)*(47 trips/week)*(52 weeks/year) = US$37 per year. This amount places a valuation on the large shifts in usage of the sample spring after protection shown in Table 4. Since there are roughly seven households members per average, this is a valuation of roughly US$5 per capita per year. This is a non-trivial welfare benefit for households in Kenya, where annual per capita income is roughly US$400. To the extent that a large part of the benefits of improved source quality water works through improving child health outcomes, this finding of moderate valuation of spring protection appears to be consistent with the positive but small and not statistically significant child health impacts discussed above (Table 8).

The panel aspect of the data allows us to assess whether households are learning about the lack of these health benefits through time. While household valuation of spring protection rises slightly in year 2, in both the first and second years of spring protection household valuation is positive but not statistically significant (Table 9 regression 2). This pattern suggests that households are quite sophisticated, and in both years form valuations of spring protection consistent with the lack of any large observed child health gains.

Turning to the estimation of heterogeneous valuations across households, we find that households with more children under age 5 at baseline find additional walking distance to a source to be especially costly (Table 9, regression 3), as expected given the demands of child care or of carrying a small child. The benefits of protection appear to be particularly pronounced for households with more children aged 5-12 years old at baseline, although this effect is not statistically significant at traditional confidence levels. This is somewhat surprising since the epidemiological evidence is clear that the largest health gains of improved water quality are experienced by the youngest children, say those under age 3. It is possible that the non-health benefits of the protected spring – in terms of appearance or ease of water collection – are particularly attractive for this group of children, especially if they themselves are the ones collecting some household water.

Finally, there is little evidence that other child characteristics have a meaningful impact on household water source choice. The gender of household children does not have a meaningful impact on household water source choices (Table 9, regression 4), although households with more girls aged 5-12 years at baseline appear to find longer walking distances somewhat less costly, which is reasonable to the extent that girls are often tasked with collecting household water and having more young girls in the home effectively reduces collection costs. The number of children reported to be ill with diarrhea at baseline is a plausible measure of households' potential benefits from cleaner water, but households with more ill children if anything appear less likely to choose the protected source than other households (regression 5). We will seek an explanation for this apparently anomalous finding in future research.

9 Discussion and conclusion

We study spring protection, an intervention that dramatically and quite cheaply improved source water quality in a rural African setting, reducing contamination by 77% on average. We find that although 65% of these source water quality gains appear to have been translated into improvements in home water quality (for the subset of sole source user households), such water quality gains were not sufficiently large to generate substantial child health and nutrition improvements.

One possible interpretation common in the existing water literature is that source water quality improvements only translate into home water quality gains – and eventually child health gains – when there are good household hygiene practices and adequate local sanitation already in place. However, this alone does not appear to be sufficient to explain our result: we do not find any evidence that spring protection led to larger home water quality gains when hygiene knowledge or latrine coverage were better. Also, spring protection did not lead to any detectable changes in water collection, transport, or storage practices, or to changes in any other preventive health behaviors that we measured, although there were sharp changes in water source choices among some households.

The fact that the water quality gains caused by spring protection did not largely dissipate during transport and storage for the sole source user households belies the conventional wisdom that recontamination renders source water quality investments alone ineffective. Crump *et al*. (2005) find statistically significant impacts of flocculant disinfectant use on child diarrhea in an area near out study site, leading us to conclude that further study is needed to determine the relative cost-effectiveness of point-of-use water treatment and source water quality investments.

We also estimate willingness to pay for improved source water by analyzing how households change their choice of water source – and in particular, the distance they are willing to walk for water – in response to the improvements generated by spring protection. We find moderate household valuation for spring protection, on the order of US$5 per capita annually, consistent with the small (at best) child health gains we estimate in our data.

These findings are the first set of results from a larger research project by the authors whose goal is to shed light on how to best and most cost effectively provide safe drinking water in rural Africa. Future rounds of household data collection, as well as the protection of additional springs, will allow us to more precisely the child health and nutrition impacts of spring protection. Beyond spring protection, we plan to use additional randomized evaluations to investigate the role that improvements in point-of-use water technologies as well as water quantity increases can play in achieving safe drinking water, and in particular to determine whether these approaches would be most effectively employed as complements to or substitutes for source water improvements like spring protection.

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Table 1: Baseline descriptive statistics (2004 survey)

	Treatment (by 2006)		Comparison		Treatment – Comparison
	Mean (s.d.)	Obs.	Mean (s.d)	Obs.	(s.e)
<u>Panel A:</u> Spring level data					
Ln. *E. coli* MPN (CFU/ 100 ml)	3.901	98	3.768	95	0.133
	(1.955)		(1.972)		(0.283)
Water is high quality (*E. coli* MPN ≤ 1)	0.051	98	0.063	95	-0.012
					(0.034)
Water is moderate quality (*E. coli* MPN 2-100)	0.612	98	0.600	95	0.012
					(0.071)
Water is high or moderate quality (*E. coli* MPN <100)	0.663	98	0.663	95	0.000
					(0.068)
Water is poor quality (*E. coli* MPN 100-1000)	0.235	98	0.263	95	-0.028
					(0.063)
Water is very poor quality (*E. coli* ≥ 1000)	0.102	98	0.074	95	0.028
					(0.041)
Latrine density (fraction of homes with latrines)	0.851	98	0.875	95	-0.024
					(0.022)
Average diarrhea prevention knowledge score	3.041	98	3.169	95	-0.128
	(0.880)		(1.181)		(0.150)
Iron roof density (fraction of compounds with iron roof)	0.703	98	0.675	95	0.028
					(0.032)
<u>Panel B:</u> Household summary statistics					
Ln. *E. coli* MPN (CFU/ 100 ml)	3.215	733	3.326	712	-0.111
	(2.218)		(2.129)		(0.142)
Water is high quality (*E. coli* MPN ≤ 1)	0.154	733	0.115	712	0.039
					(0.019)**
Water is moderate quality (*E. coli* MPN 2-100)	0.575	733	0.621	712	-0.046
					(0.030)
Water is high or moderate quality (*E. coli* MPN <100)	0.729	733	0.736	712	-0.007
					(0.029)
Water is poor quality (*E. coli* MPN 100-1000)	0.202	733	0.188	712	0.014
					(0.025)
Water is very poor quality (*E. coli* ≥ 1000)	0.07	733	0.076	712	-0.006
					(0.014)
Respondent years of education	5.706	731	5.658	717	0.048
	(3.608)		(3.598)		(0.226)
Children under age 12 in the compound	4.00	736	3.88	719	0.12
	(2.53)		(2.53)		(0.15)
Iron roof indicator	0.703	735	0.675	717	0.028
					(0.032)
Walking distance to closest water source (minutes)	10.259	713	9.596	698	0.663
	(9.995)		(8.770)		(0.653)
Water collection trips per week by household	47.98	733	48.07	712	-0.09
	(36.46)		(38.47)		(2.52)

	Treatment (by 2006)		Comparison		Treatment – Comparison
	Mean (s.d.)	Obs.	Mean (s.d)	Obs.	(s.e)
Ever collects drinking water at "assigned" spring indicator	0.823	661	0.804	668	0.019 (0.033)
Multi source user (uses sources other than assigned spring)	0.448	732	0.447	715	0.001 (0.042)
Fraction of respondent trips to "assigned" spring	0.719	655	0.704	663	0.015 (0.035)
Rates spring water "very clean" (rainy season)	0.327	736	0.325	719	0.002 (0.035)
Rates water at spring "very clean" (dry season)	0.736	736	0.741	719	-0.005 (0.033)
Fraction of water trips by those under age 12	0.101	733	0.105	712	-0.004 (0.011)
Water storage container in home was covered	0.897	672	0.930	656	-0.033 (0.016)**
Yesterday's drinking water was boiled indicator	0.252	731	0.286	711	-0.034 (0.024)
Respondent diarrhea prevention knowledge score	2.84 (2.19)	736	2.95 (2.23)	719	-0.109 (0.205)
Respondent said dirty water causes diarrhea	0.681	736	0.668	719	0.013 (0.027)
Household compound is clear of debris	0.525	734	0.536	716	-0.012 (0.034)
Household has soap in the home	0.911	733	0.908	717	0.003 (0.016)
Panel C: Child demographics and health					
Child age§	1.71 (0.95)	1045	1.72 (0.97)	994	-0.017 (0.035)
Child gender (=1 if male)	0.519	1045	0.504	993	0.015 (0.024)
Child had diarrhea in past week indicator	0.235	996	0.206	956	0.029 (0.022)
Child weight (cm)	9.99 (11.63)	867	10.02 (12.14)	831	-0.03 (0.16)
Child height (kg)	76.14 (9.99)	861	76.12 (10.02)	806	0.02 (0.57)

Notes: In the final column, Huber-White robust standard errors are presented (clustered at spring level when using household level data), significantly different than zero at * 90% ** 95% *** 99% confidence.
Standard deviations not presented for indicator variables.
Diarrhea is defined as three or more "looser than normal" stools per day.
Assigned spring is the spring that we believed households used at baseline, based on spring user lists.
Household survey respondent is the mother of the youngest child in the compound (or the next youngest woman available).
§ All children in the sample in Panel C were reported to be under age 3 at baseline.

Table 2: Spring protection source water quality impacts, difference-in-differences

	Panel A: Dependent variable, Ln(Spring *E. coli* MPN) 2005 (round 1 post-treatment)			Panel B: Dependent variable, Spring water high quality (*E. coli* MPN ≤ 1) 2005 (round 1 post-treatment)		
	Treatment, mean (s.d.)	Comparison, mean (s.d.)	T – C (s.e.)	Treatment, mean (s.d.)	Comparison, mean (s.d.)	T – C (s.e.)
Treatment Group 1, mean (s.d.)	3.97	3.81	0.16	0.06	0.05	0.01
	(2.09)	(1.90)	(0.35)			(0.04)
After protection, mean (s.d.)	2.64	3.77	-1.13	0.17	0.05	0.12
	(2.19)	(1.86)	(0.36)***			(0.06)**
After – Before difference (s.e.)	-1.33	-0.04	-1.29	0.11	-0.00	0.11
	(0.44)***	(0.19)	(0.48)***	(0.07)*	(0.03)	(0.07)
% Change in contamination	-74%	-4%	-72%			
	Panel C: Dependent variable, Ln(Spring *E. coli* MPN) 2006 (round 2 post-treatment)			Panel D: Dependent variable, Spring water high quality (*E. coli* MPN ≤ 1) 2006 (round 2 post-treatment)		
	Treatment, mean (s.d.)	Comparison, mean (s.d.)	T – C (s.e.)	Treatment, mean (s.d.)	Comparison, mean (s.d.)	T – C (s.e.)
Treatment Groups 1 & 2, mean (s.d.)	3.92	3.79	0.13	0.05	0.07	-0.02
	(1.96)	(1.93)	(0.30)			(0.04)
After protection, mean (s.d.)	2.25	3.59	-1.34	0.29	0.14	0.15
	(2.09)	(2.21)	(0.33)***			(0.06)**
After – Before difference (s.e.)	-1.66	-0.20	-1.46	0.24	0.07	0.18
	(0.29)***	(0.27)	(0.39)***	(0.05)***	(0.04)*	(0.07)***
% Change in contamination	-81%	-18%	-77%			

Notes: N=174 springs. Huber-White robust standard errors (clustered at the spring level) are presented, significantly different than zero at * 90% ** 95% *** 99% confidence. MPN stands for “most probable number” coliform forming units (CFU) per 100ml. Standard deviations not reported for indicator variables. Percent change in contamination calculated as -(1-exp(After – Before difference) * 100.

Table 3: Spring protection source water quality impacts, regression specifications

	Dependent variable: ln(Spring water *E. coli* MPN)			
	(1)	(2)	(3)	(4)
Treatment (protected) indicator	-1.06	-1.06	-0.97	-1.01
	(0.33)***	(0.33)***	(0.28)***	(0.29)***
Baseline ln(Spring water *E. coli* MPN)		0.49	0.97	0.98
		(0.04)***	(0.04)***	(0.04)***
Baseline ln(Spring water *E. coli* MPN)			-0.30	-0.28
* Treatment indicator			(0.15)**	(0.15)*
Baseline latrine density				-0.09
				(0.59)
Baseline latrine density * Treatment indicator				0.66
				(2.23)
Baseline diarrhea prevention score				-0.06
				(0.06)
Baseline diarrhea prevention score*Treatment indicator				-0.23
				(0.32)
Baseline iron roof density				1.02
				(0.43)**
Baseline iron roof density * Treatment indicator				1.14
				(1.82)
Treatment group 1 (2004)	-0.22	-0.31	-0.36	-0.37
	(0.32)	(0.20)	(0.16)**	(0.17)**
Treatment group 2 (2005)	-0.21	-0.23	-0.26	-0.24
	(0.26)	(0.17)	(0.16)	(0.17)
R^2	0.14	0.33	0.44	0.46
Observations	522	522	522	522
Mean (s.d.) of dependent variable	3.79 (1.93)	3.79 (1.93)	3.79 (1.93)	3.79 (1.93)

Notes: Estimated using OLS. Huber-White robust standard errors are presented (clustered at the spring level), significantly different than zero at * 90% ** 95% *** 99% confidence. There are 174 spring clusters with data for the three survey rounds (2004, 2005, 2006). MPN stands for “most probable number” coliform forming units (CFU) per 100ml.

Average diarrhea prevention knowledge calculated as average of demeaned sum of number of correct responses given to the open ended question “to your knowledge what can be done to prevent diarrhea?”

All variables that are interacted with the treatment indicator are de-meaned.

Time fixed effects included in all regressions but not reported. When interactions included, baseline variables are interacted with time dummies and treatment group dummies in addition to treatment indicator. These coefficients not reported.

Table 4: Treatment effects on household water source choice and health behaviors

	Coefficient (s.e.) on treatment indicator Full sample	Coefficient (s.e.) on treatment indicator Sole source users	Coefficient (s.e.) on treatment indicator Multi-source users	Mean (s.d.) comparison group in 2006 survey, Full sample
Dependent variable	(1)	(2)	(3)	(4)
Panel A: Water collection and source choice				
Use assigned spring for drinking water indicator	0.07 (0.06)	-0.00 (0.05)	0.21 (0.08)***	0.56
Fraction of trips to assigned spring	0.05 (0.05)	-0.01 (0.05)	0.19 (0.07)***	0.47
Perceive water at assigned spring to be very clean (rainy season)	0.24 (0.04)***	0.24 (0.05)***	0.23 (0.05)***	0.18
Perceive water at assigned spring to be very clean (dry season)	0.12 (0.04)***	0.08 (0.04)**	0.16 (0.06)***	0.75
Distance to nearest water (min.)	-1.18 (0.53)**	-1.90 (0.60)***	-0.16 (0.90)	7.28 (5.97)
Trips made to get water (all uses, members, sources) past week	0.09 (2.17)	-0.29 (2.40)	0.45 (3.59)	26.11 (14.58)
Panel B: Water transportation and storage				
Fraction of water trips by those under age 12 (a)	-0.01(0.05)	0.01(0.04)	-0.03(0.08)	0.08
Water storage container in home covered indicator	-0.00 (0.01)	-0.02 (0.02)	0.02 (0.02)	0.97
Ever treat water with chlorine indicator (b)	0.05 (0.05)	0.10 (0.06)	0.01 (0.06)	0.27
Yesterday's drinking water boiled indicator	0.06 (0.03)**	0.10 (0.05)**	0.02 (0.04)	0.25
Panel C: Complementary sanitation and hygiene behaviors				
Diarrhea prevention knowledge score	0.21 (0.15)	0.16 (0.21)	0.26 (0.19)	4.00 (2.04)
Respondent says drinking clean water is a way to prevent diarrhea	-0.03 (0.03)	-0.02 (0.04)	-0.04 (0.04)	0.75
Household compound is clear of debris indicator	0.04 (0.04)	0.04 (0.05)	0.04 (0.05)	0.74
Household has soap in the home indicator	-0.00 (0.02)	-0.03 (0.03)	0.02 (0.03)	0.89
Panel D: Spring amenities (recorded by enumerators)				
Spring has "clear" water	0.23 (0.08)***	-	-	0.74
Fence around spring	0.96 (0.03)***	-	-	0.00
Spring has "high" water yield	0.00 (0.08)	-	-	0.63
Fecal matter around spring	-0.31 (0.08)***	-	-	0.53
Animals around spring	-0.10 (0.06)*	-	-	0.14

Trees planted around spring	0.00 (0.04)	-	-	1.97
Trench for spring water cleared in last month	0.29 (0.12)**	-	-	0.59
Vegetation near spring cleared in last month	0.34 (0.09)***	-	-	0.47
Measure of reported spring maintenance quality (1=excellent, 5=poor)	-0.73 (0.20)***	-	-	3.12 (1.03)

Notes: N=1023 households at 174 springs with complete data (full sample), and 590 households are sole source users. Each cell reports the differences-in-differences treatment effect estimate from a separate regression, where dependent variable is reported in first column. Huber-White robust standard errors (clustered at the spring level) are presented, significantly different than zero at * 90% ** 95% *** 99% confidence.
Standard deviations of the dependent variable not reported for indicator variables.
Reported means of the dependent variables are in the comparison group 2006 (round 2 post-treatment) survey.
Assigned spring is the spring that we believed households used at baseline based on spring user lists.
(a): Because of changes in survey design, responses to this question are available only for the first (2004) and second (2005) round of data collection.
(b): Because of changes in survey design, responses to this question are available only for the second (2005) round of data collection.

Table 5: Spring protection household water quality impacts, difference-in-differences

	Panel A: Full sample, 2005 Dependent variable: ln(*E. coli* MPN)			Panel B: Full sample, 2006 Dependent variable: ln(*E. coli* MPN)		
	Treatment, mean (s.d.)	Comparison, mean (s.d.)	T – C (s.e.)	Treatment, mean (s.d.)	Comparison, mean (s.d.)	T – C (s.e.)
Before protection, mean (s.d.)	3.37	3.22	0.15	3.27	3.25	0.02
	(2.29)	(2.13)	(0.18)	(2.27)	(2.08)	(0.16)
After protection, mean (s.d.)	3.13	3.35	-0.22	2.81	3.09	-0.28
	(2.14)	(2.11)	(0.17)	(2.21)	(2.24)	(0.16)*
After – Before difference (s.e.)	-0.24	0.13	-0.37	-0.46	-0.16	-0.30
	(0.20)	(0.11)	(0.23)	(0.16)***	(0.16)	(0.22)
% Change in contamination	-21%	14%	-31%	-37%	-15%	-26%
	Panel C: Sole Source Spring Users, 2005 Dependent variable: ln(*E. coli* MPN)			Panel D: Sole Source Users, 2006 Dependent variable: ln(*E. coli* MPN)		
	Treatment, mean (s.d.)	Comparison, mean (s.d.)	T – C (s.e.)	Treatment, mean (s.d.)	Comparison, mean (s.d.)	T – C (s.e.)
Before protection, mean (s.d.)	3.61	3.21	0.40	3.35	3.30	0.05
	(2.32)	(2.10)	(0.24)*	(2.26)	(2.07)	(0.20)
After protection, mean (s.d.)	3.12	3.46	-0.34	2.81	3.20	-0.39
	(2.09)	(2.04)	(0.21)	(2.27)	(2.15)	(0.21)*
After – Before difference (s.e.)	-0.50	0.24	-0.74	-0.54	-0.09	-0.44
	(0.25)*	(0.14)*	(0.28)***	(0.19)***	(0.21)	(0.28)
% Change in contamination	-39%	27%	-52%	-42%	-9%	-36%
	Panel E: Multi-source Spring Users, 2005 Dependent variable: ln(*E. coli* MPN)			Panel F: Multi-source Spring Users, 2006 Dependent variable: ln(*E. coli* MPN)		
	Treatment, mean (s.d.)	Comparison, mean (s.d.)	T – C (s.e.)	Treatment, mean (s.d.)	Comparison, mean (s.d.)	T – C (s.e.)
Before protection, mean (s.d.)	3.04	3.23	-0.19	3.17	3.19	-0.02
	(2.22)	(2.17)	(0.24)	(2.27)	(2.10)	(0.23)
After protection, mean (s.d.)	3.13	3.22	-0.09	2.79	2.94	-0.15
	(2.21)	(2.18)	(0.23)	(2.11)	(2.35)	(0.22)
After – Before difference (s.e.)	0.09	-0.01	0.10	-0.38	-0.24	-0.13
	(0.24)	(0.17)	(0.29)	(0.22)*	(0.20)	(0.30)
% Change in contamination	9%	-1%	11%	-32%	-21%	-12%

Notes: N = 1105 households at 174 springs with complete data, and 607 households are sole source users. Huber-White robust standard errors are presented (clustered at the spring level), significantly different than zero at * 90% ** 95% *** 99% confidence. Standard deviation not reported for indicator variables. Percent change in contamination calculated as -(1-exp(After – Before difference) * 100

Table 6: Spring protection household water quality impacts, regression specifications

	Dependent variable: ln(Home water *E. coli* MPN)		
	(1)	(2)	(3)
Treatment (protected) indicator	-0.37	-0.49	-0.74**
	(0.17)**	(0.21)**	(0.30)
Baseline ln(Spring water *E. coli* MPN)	0.07	0.08	0.08***
	(0.02)***	(0.02)***	(0.02)
Baseline multi-source user		-0.21	-0.21
		(0.19)	(0.19)
Baseline multi-source user * Treatment indicator		0.28	0.30
		(0.27)	(0.276)
Baseline diarrhea prevention score	-0.01	-0.01	-0.06
	(0.02)	(0.02)	(0.04)
Baseline diarrhea prevention score * Treatment indicator			-0.027
			(0.065)
Baseline latrine density	-0.80	-0.82	-0.22
	(0.36)**	(0.35)**	(0.64)
Baseline latrine density * Treatment indicator			1.06
			(1.21)
Baseline boiled water yesterday indicator	0.10	0.09	0.21
	(0.09)	(0.09)	(0.17)
Baseline boiled water yesterday indicator * Treatment indicator			0.27
			(0.32)
Treatment group 1 (phased in early 2005)	0.12	0.12	0.11
	(0.16)	(0.21)	(0.32)
Treatment group 2 (phased in late 2005)	-0.06	-0.10	-0.15
	(0.12)	(0.17)	(0.30)
R^2	0.03	0.03	0.04
Observations (spring clusters)	3282 (174)	3282 (174)	3282 (174)
Mean (s.d.) of dependent variable in comparison group, 2006	3.09 (2.26)	3.09 (2.26)	3.09 (2.26)

Notes: Estimated using OLS. Huber-White robust standard errors (clustered at the spring level) are presented, significantly different than zero at * 90% ** 95% *** 99% confidence. MPN stands for "most probable number" coliform forming units (CFU) per 100ml.

Additional control variables included are: season fixed effects, number of children under 12 living in the home, mother's years of education, home has iron roof indicator, iron roof density within spring community. When differential treatment effects are reported in column 3, we also include interactions with all of these control variables and the treatment indicator (not shown in the table). Baseline spring water quality, latrine density, and diarrhea prevention score are de-meaned.

Time fixed effects included in all regressions but not reported. When interactions are included, baseline variables are interacted with time effects and treatment group indicators, in addition to interactions with treatment (protected) indicator. These coefficients not reported in the table.

Table 7: The elasticity of household water quality with respect to spring water quality

	Dependent variable: ln(Home water *E. coli* MPN)		
	Full sample	Sole-source users	Sole-source users
	OLS	OLS	IV
	(1)	(2)	(3)
ln (Spring water *E. coli* MPN)	0.22***	0.23***	0.66**
	(0.02)	(0.03)	(0.31)
Diarrhea prevention knowledge score	-0.010	-0.046*	-0.046
	(0.021)	(0.028)	(0.032)
Latrine density	-0.72**	-1.14**	-1.18*
	(0.35)	(0.51)	(0.64)
Baseline boiled water yesterday indicator	0.111	0.135	0.147
	(0.095)	(0.111)	(0.126)
District-wave (season) fixed effects	Yes	Yes	Yes
R^2	0.06	0.08	--
Observations (spring clusters)	3282 (174)	1803 (159)	1803 (159)
Mean (s.d.) of dep. var. in comparison group	3.09 (2.26)	3.22 (2.14)	3.22 (2.14)

Notes: Huber-White robust standard errors (clustered at the spring level) are presented, significantly different than zero at * 90% ** 95% *** 99% confidence. MPN stands for “most probable number” coliform forming units (CFU) per 100ml. All continuous variables are demeaned. Diarrhea prevention knowledge calculated as sum of number of correct responses given to the open ended question “to your knowledge what can be done to prevent diarrhea. Additional controls included in columns 1-3 are: number of children in home compound, respondent’s years of education, iron roof indictor and iron roof density in the spring community. Time and treatment group fixed effects are also included in columns 1-3. The instrumental variable in column 3 is the treatment (protection) indicator.

Table 8: Child health outcomes for children under age three at baseline or born since 2004

	Dependent variable: Diarrhea in past week			Dependent variable: Weight (kg.)			Dependent variable: Height (cm.)		
	(1)	(2)	(3)	(4)	(5)	(6)	(7)	(8)	(9)
Treatment (protected) indicator	-0.026	-0.012	-0.027	0.211	0.136	0.198	-0.808	-0.405	-0.828
	(0.036)	(0.042)	(0.036)	(0.331)	(0.368)	(0.325)	(0.508)	(0.582)	(0.521)
Baseline multi-source user * Treatment indicator		-0.034			0.166			-0.871	
		(0.053)			(0.305)			(0.841)	
Treatment (protected) indicator, Year 2 of protection			0.011			0.237			0.380
			(0.034)			(0.481)			(0.690)
Child fixed effects?	Yes	Yes	Yes	Yes	Yes	Yes	Yes	Yes	Yes
R^2	0.57	0.57	0.55	0.80	0.80	0.78	0.97	0.97	0.97
Child-year observations	5537	5537	5537	3655	3655	3655	3795	3795	3795
Mean (s.d.) of the dep. var. in comparison group	0.18	0.18	0.18	11.71	11.71	11.71	82.54	82.54	82.54
				(4.33)	(4.33)	(4.33)	(16.46)	(16.46)	(16.46)

Notes: Estimated using OLS. Huber-White robust standard errors (clustered at the spring level) are presented, significantly different than zero at * 90% ** 95% *** 99% confidence. Data from all three survey rounds (2004, 2005, 2006), sample restricted to children under age three at baseline (in 2004) and children born since 2004. 61 severe height outliers excluded. Diarrhea defined as three or more “looser than normal” stools within 24 hours at any time in the past week.

Table 9: Conditional logit estimates of water source choice (2004, 2005, 2006 surveys)

	(1)	(2)	(3)	(4)	(5)
Distance to water source (minutes walking)	-0.023***	-0.023**	-0.017***	-0.017***	-0.017***
	(0.0027)	(0.0027)	(0.0046)	(0.0045)	(0.0046)
Treatment (protected) indicator	0.084	0.068	-0.153	-0.144	-0.191
	(0.116)	(0.136)	(0.222)	(0.226)	(0.218)
Treatment (protected) indicator, Year 2 of protection		0.065			
		(0.219)			
Distance to water source (minutes walking) * Children aged 0-5 at baseline			-.0036**	-0.0028	-0.0017
			(0.0015)	(0.0023)	(0.0039)
Distance to water source (minutes walking) * Children aged 5-12 at baseline			0.0001	-0.0023	0.0002
			(0.0019)	(0.0027)	(0.0020)
Treatment indicator * Children aged 0-5 at baseline			0.0099	-0.094	0.449**
			(0.057)	(0.093)	(0.199)
Treatment indicator * Children aged 5-12 at baseline			0.118	0.114	0.131*
			(0.076)	(0.117)	(0.073)
Distance to water source (minutes walking) * Girls aged 0-5 at baseline				-0.0017	
				(0.0040)	
Distance to water source (minutes walking) * Girls aged 5-12 at baseline				0.0047	
				(0.0032)	
Treatment indicator * Girls aged 0-5 at baseline				0.162	
				(0.110)	
Treatment indicator * Girls aged 5-12 at baseline				0.020	
				(0.144)	
Distance to water source (minutes walking) * Children aged 0-5 at baseline, diarrhea in last week					-0.0022
					(0.0041)
Treatment indicator * Children aged 0-5 at baseline, diarrhea in last week					-0.462**
					(0.203)
Source type: Program spring	0.05	0.05	0.05	0.06	0.05
	(0.07)	(0.07)	(0.07)	(0.07)	(0.07)
Source type: Well	0.36***	0.36***	0.36***	0.36***	0.34***
	(0.12)	(0.12)	(0.12)	(0.12)	(0.12)
Source type: Borehole	0.12	0.12	0.10	0.11	0.11
	(0.11)	(0.11)	(0.11)	(0.11)	(0.11)
Source type: Stream/river	-0.32**	-0.32**	-0.33**	-0.34**	-0.34**
	(0.14)	(0.14)	(0.14)	(0.14)	(0.14)
Log pseudo-likelihood	-384.18	-384.17	-344.86	-344.52	-344.45
Number of households	760	760	759	759	758
Number of observations	114599	114599	114256	114256	114256

Notes: Disturbance terms are clustered by spring, significantly different than zero at * 90% ** 95% *** 99% confidence. Each observation represents a unique household-water source pair, in a given water collection trip. The data are from all three rounds of household surveys (2004, 2005, 2006). The results are from a conditional logit model (grouped at the trip level). The dependent variable is an indicator that equals 1 if the households chose the source represented in that household-water source pair in that water collection trip. The omitted water source category is “spring”.

Figure 1: Map of study region

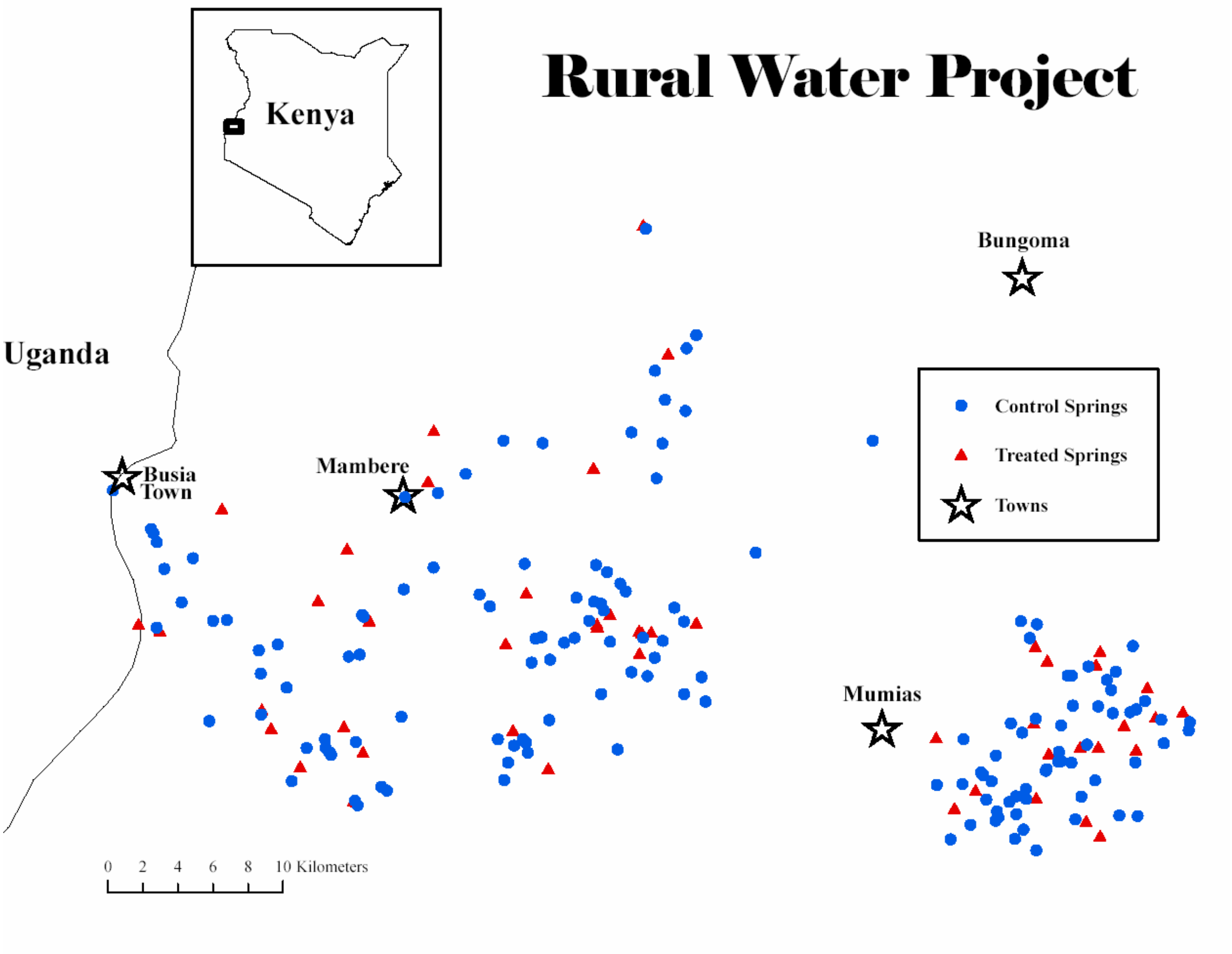


Figure 2: Timeline of Rural Water Project (RWP) Activities 2004-2006

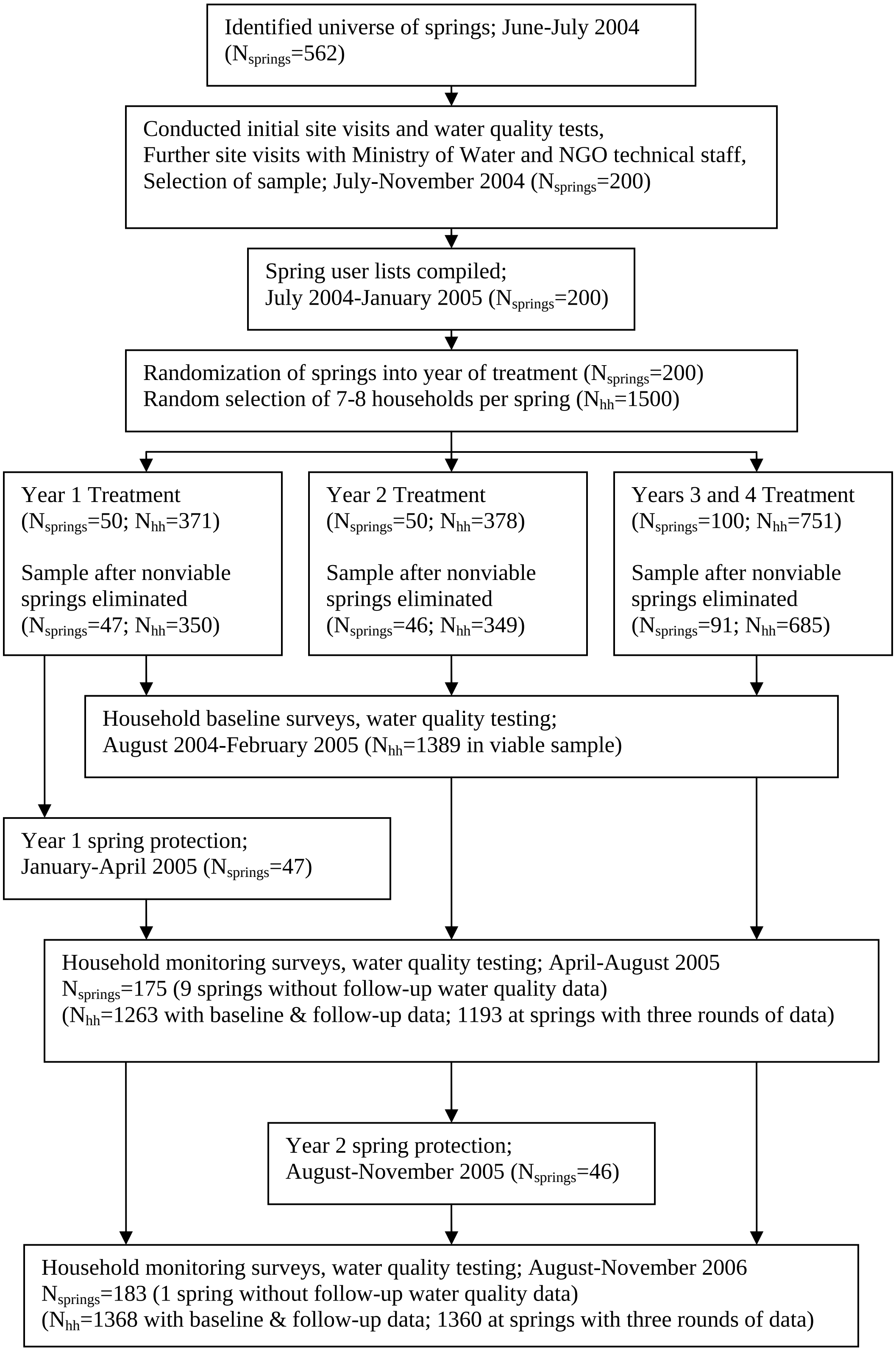
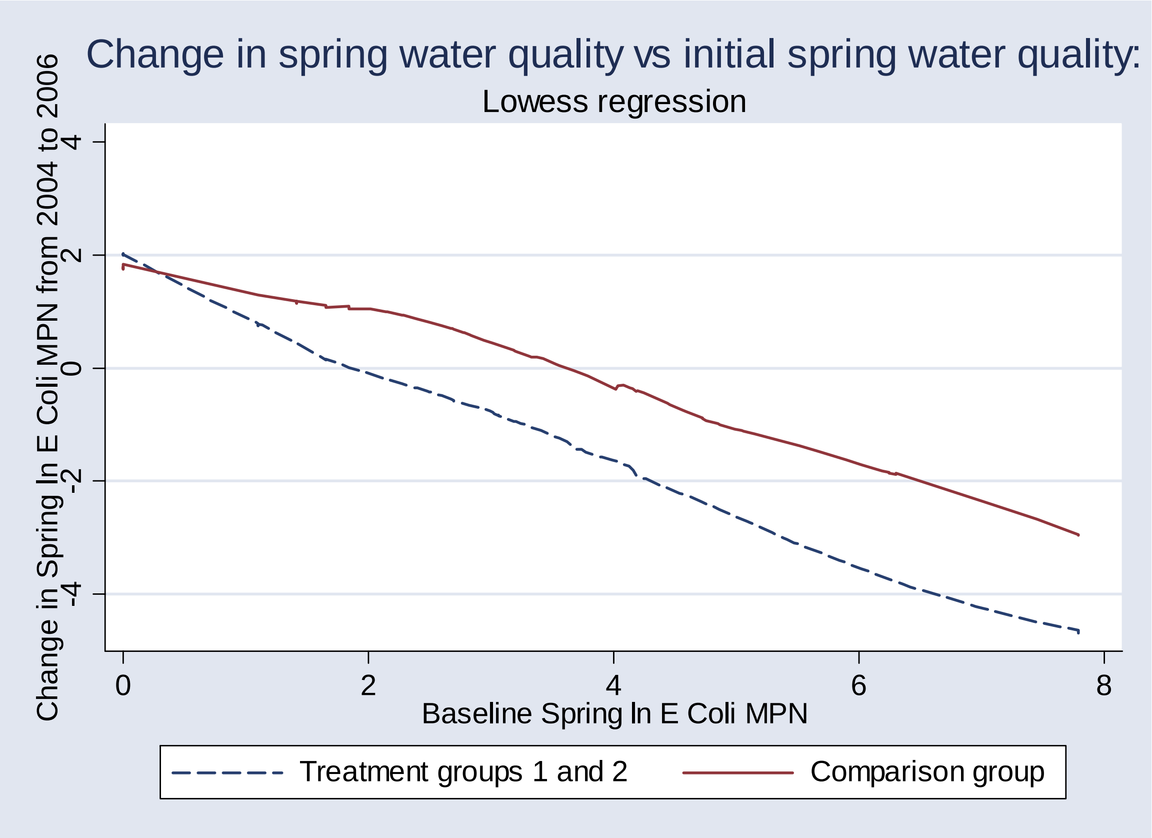


Figure 3: Change in water contamination from 2004 to 2006
versus baseline (2004) water contamination



Notes: To 10-90 range in Baseline ln (*E Coli* MPN) is [1.13, 6.31].
MPN stands for “most probable number” coliform forming units (CFU) per 100ml.